World trade and the environment: Essays on economic structure,international supply chains, and environmental impact

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URL	http://hdl.handle.net/10097/58511

World trade and the environment:

Essays on economic structure, international supply chains, and environmental impact

Keiichiro Kanemoto

Abstract

In the first chapter, co-authored with Joy Murray, we introduced development, history, benefits, and limitations of multi-region input-output (MRIO) analysis.

In the second chapter, co-authored with Manfred Lenzen, Glen P. Peters, Daniel Moran, and Arne Geschke, we critically examine a number of emissions accounting concepts, examine whether the ensuing carbon balances are compatible with monetary trade balances, discuss their different interpretations, and highlight implications for policy. In particular, we compare the emissions embodied in bilateral trade (EEBT) method which considers total trade flows with domestic emission intensities, with the multi-region input-output (MRIO) method which considers trade only into final consumption with global emission intensities.

In the third chapter, co-authored with Manfred Lenzen, Daniel Moran, and Arne Geschke, we have developed a series of new environmentally extended multi-region input-output table with applications in carbon, water and ecological footprinting, Life-Cycle Assessment (LCA), as well as trend and key driver analyses. Such applications have recently been at the forefront of global policy debates, such as about assigning responsibility for emissions embodied in internationally traded products. The new times series was constructed using

advanced parallelized supercomputing resources, and significantly advances the previous state of art.

In the fourth chapter, co-authored with Daniel Moran, Manfred Lenzen, and Arne Geschke, we investigate emission leakage caused by Kyoto Protocol. Many developed countries in Annex B of the Kyoto Protocol have been able to report decreasing emissions, and some have officially fulfilled their CO_2 reduction commitments. This is in part because current reporting and regulatory regimes allow these countries to displace emissions intensive production offshore. Using a new highly detailed account of emissions embodied in international trade we investigate this phenomenon of emissions leakage. We independently confirm previous findings that adjusting for trade, developed countries emissions have increased, not decreased. We find that the sectors successfully holding or lowering their domestic emissions are often the same as those increasing their imports of embodied CO_2. We also find that the fastest growing flow paths of embodied CO_2 largely originate outside the Kyoto Annex B signatory nations. Finally, we find that historically the same phenomenon of emissions displacement has already occurred for air pollution, with the result that despite aggressive legislation in major emitters total global air pollution emissions have increased. If regulatory policies do not account for embodied imports, global emissions are likely to rise even if developed countries emitters enforce strong national emissions targets.

In the final chapter, we summarize our findings.

Acknowledgements

I am deeply grateful to Manfred Lenzen for his support, advice, and encouragement. Since I was undergraduate student, he invited me to Integrated Sustainability Analysis (ISA), The University of Sydney, gave me the opportunity to join ISA and Eora project, and provided significant suggestions for improving the dissertation. I also would like to express my gratitude to Daniel Moran and Arne Geschke for their encouragements and sound advice in many conversations. I have had with them over the last few years. I would not have been able to complete this thesis without collaboration with them.

I am indebt to the member of dissertation committee for their supports and accessibility. Jusen Asuka and Atsushi Ishii have been supporting college life and providing suggestions for improving the dissertation. Additionally, I would like to gratefully and sincerely thank Keisuke Nansai and Shigemi Kagawa for agreeing to serve on my dissertation committee and their scientific suggestions and helpful career advice.

Discussions and supports with numerous collaborators and colleagues have contributed to the development of my work. I would like to thank Joy Murray, Jodie Gonzalez Jennings, Christopher Dey, Glen P. Peters, Thomas Wiedmann, Yasushi Kondo, Kazuyo Matsubae-Yokoyama, Yutaka Tonooka, Hiroki Hondo, Satoshi Inomata, Norihiko Yamano, Richard Wood, Pablo Munõz, Jun Lan, Chia-Hao Liu, Jessica Dielmann, Olivier Baboulet, Ting Yu, Darian McBain, Barney Foran, Bonnie McBain, Julien Ugon, Ali Alsamawi, Erik Dietzenbacher, Sagwon Suh, Arnold Tukker, Edgar Hertwich, Bart Los, James West, Heinz Schandl, Lobefaro Leonarda, Masataka Fujita, Bo Werth, Colin Webb, Nadim Ahmad, Guannan Miao, Kiyotaka Tahara, Kotaro Kawajiri, Masanobu Ishikawa, Hideyoshi Sakai, Kenichi Nakajima, Li Jie, Kazunori Nakajima, Wataru Machida, Shunsuke Managi, Shigeaki Fujisaki, Shunsuke Mori, Norihisa Sakurai, Yuko Oshita, Masafumi Umemura, and Shinichiro Asayama.

Finally I acknowledge fellowship support from the Japan Society for the Promotion of Science and funding support from the Australian Research Council (ARC) under its Discovery Project DP0985522 and its Linkage Project LP0669290.

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1. Introduction: MRIO benefits & limitations

The extension of globalization over the last few decades has generated not only economic growth but also side effects. International trade has grown rapidly compared to other major indicators such as GDP (gross domestic product), population, and CO_2 emission (Fig. 1.1). Exports of goods and services are about 49 times larger today than they were in 1970. We have changed our economic, social, and environmental perspectives from the local to the global level as a result of globalization. Expansion of international trade has changed our production and consumption patterns completely, and has generated wide-ranging side effects. For example, Westphal, Browne, MacKinnon, & Noble (2008) found the greater the degree of international trade, the higher the number of invasive alien species.

Another recent interest for consumers, researchers, and companies is supply chain and life cycle thinking. These groups have changed our focus from the goods themselves to the processes involved in developing and transporting those goods. For example, food companies have started to show not only the calories and ingredients but also the food mileage and genetic-modification on the label of foods, and this information at least affects consumers indirectly (Miles, Ueland, & Frewer, 2005). Numerous studies on bottom-up life cycle assessment (LCA) have been conducted on various products (Finnveden et al., 2009; Roy et al., 2009), but bottom-up LCA cannot cover the whole economy and all production stages (Lenzen, 2001; Lenzen & Treloar, 2006) Therefore an input-output approach has been used as a tool of top-down LCA.

The existing environmental analyses such as testing environmental Kuznets curve hypothesis have not considered changes in the economic and technological system. Even though the manufacturing process and the contents of goods and services have drastically changed in the last few decades, we have still use same names for these products.

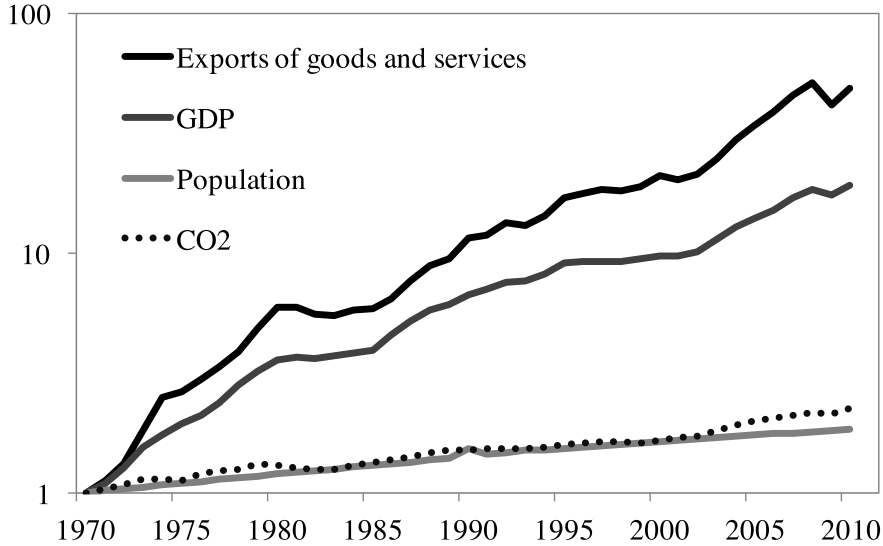

Fig. 1.1: The growth of world exports of goods and services, GDP, population, and CO_2 emission from 1970 to 2010 (1970 = 1) (Boden, Marland, & Andres., 2011; Friedlingstein et al., 2010; United Nations, 2012).

Against the background of these three changes, multi-region input-output (MRIO) analysis is emerging as a way to analyze the global supply chain (Wiedmann, 2009). There are several initiatives underway to construct global MRIO tables (Erumban et al., 2011; EXIOPOL, 2008; Lenzen, Kanemoto, Moran, & Geschke, 2012; Peters, Andrew, & Lennox, 2011; Timmer, 2012; Tukker et al., 2009; WIOD, 2010), and several studies using MRIO have been published in top journals recently (Davis & Caldeira, 2010; Davis et al., 2011; Lenzen et al., 2012; Peters, Marland, Le Quéré, et al., 2011; Peters, Minx, Weber, & Edenhofer, 2011b; Steinberger et al., 2012). These studies have mainly focused on global carbon footprints and consumption-based national CO_2 emissions, but there are plenty of opportunities to analyze global MRIO with other environmental and social indicators and other scales of MRIO (Kanemoto, Moran, Lenzen, & Geschke, 2013; Lenzen, Moran, Kanemoto, Foran, et al., 2012; Nijdam, Wilting, Goedkoop, & Madsen, 2005; Weber & Matthews, 2007; Wiedmann et al., 2013; Zhou & Imura, 2011). Applications of MRIO are getting underway, so the needs of MRIO to global governance will increase in the near future (Murray & Lenzen, n.d.).

In this chapter, we introduce the concept and a short history followed by the benefits and limitations of MRIO.

1.1. Concept and history of MRIO

The single-region input-output (SRIO) table that is published by central and local governments includes one region's intermediate demand, final demand, exports, imports, and value added across a certain number of industries and commodities. The SRIO model allows us to analyze only the supply chain within one region, because single region IO tables do not report on what happens to exported goods or services once they are exported or how much pollution is emitted in the making of imported goods or services imported from another region. In MRIO tables, exported goods and services from one region are treated as inputs to industries in other regions, and imported goods and services of one region pass through other regions' production processes. Therefore, we can trace the supply chain between regions. All of MRIO analysis, footprint analysis, and interregional LCA share the common aim of tracing supply chain, thus the MRIO analysis has been seen as a promising approach to apply environmental problems.

In Fig. 1.2 we show an example of a two-regional input-output table with two sectors: goods and services. The highlighted column means Region 1's Service sector buys 10 units of Goods and 20 units of Services from Region 1, imports 10 units of Services from Region 2, and pays 5 units to value added to make Services. The highlighted row means Region 2 exports 30 and 15 units of Goods to the Goods sector and to final demand of Region 1; and sells 20 units of Goods to the Goods sector and 10 units to final demand of Region 2. Therefore the total export of Goods from Region 2 to Region 1 is 45 units.

		Region 1		Region 2		Final demand	
		Goods	Services	Goods	Services	Region 1	Region 2
Region 1	Goods	100	10	5	0	30	0
	Services	0	20	0	0	20	5
Region 2	Goods	30	0	20	0	15	10
	Services	10	10	0	5	0	10
Value added		5	5	50	30		

Fig. 1.2: Example of two-regional input-output table

Constructing an MRIO table is not a complex task, but it is data-hungry and computationally intensive. Therefore, global-scale MRIO tables were not constructed until around 2008. MRIO tables consist of domestic and interregional trade blocks (Fig. 1.3). SRIO tables are used to build the domestic trade blocks of the MRIO table for each region. National Statistical Offices regularly conduct industry surveys to compile SRIO tables of their own country. However, official statistics on the interaction of regional trade blocks often don't exist so several ways to estimate interregional trade blocks in MRIO tables have been developed. One way is to survey industries directly to find out which industries or sectors of the economy (which could be households) use imported commodities from which countries. For example the UK might import cars from Japan and Germany. However unless we actually survey to find out who buys which cars we cannot know where the German manufactured cars end up and where the Japanese ones go. Surveying increases the accuracy in tracing supply chains. It is particularly important where there are significant differences in the way the product is manufactured in different countries. Another way to estimate interregional trade blocks in MRIO tables is known as the non-survey method, or trade coefficient approach. It is a way of constructing interregional trade blocks without surveying to find out which industries use imported commodities from which countries. In the non-survey method, import tables are disaggregated into a certain number of trade blocks using bilateral trade statistics (e.g. Lenzen et al., 2010; Oosterhaven, Stelder, & Inomata, 2008; Stevens, Treyz, And, & Bower, 1983). However, to continue the example above, this method will not tell you exactly who buys which cars. It will tell you what percent of imported cars come from Germany and what percent come from Japan. These will then be lumped together as *imported cars* and pro-rated according to the percentage of imported cars bought by households, government or various other sectors of the economy irrespective of where they originated.

Whichever method is chosen matrix balancing should always be conducted on MRIO tables to fulfil the general economic theory that gross input, such as raw materials and wages, is equal in monetary value to gross output such as household consumption. This is the same process as we apply to the construction of SRIO tables.

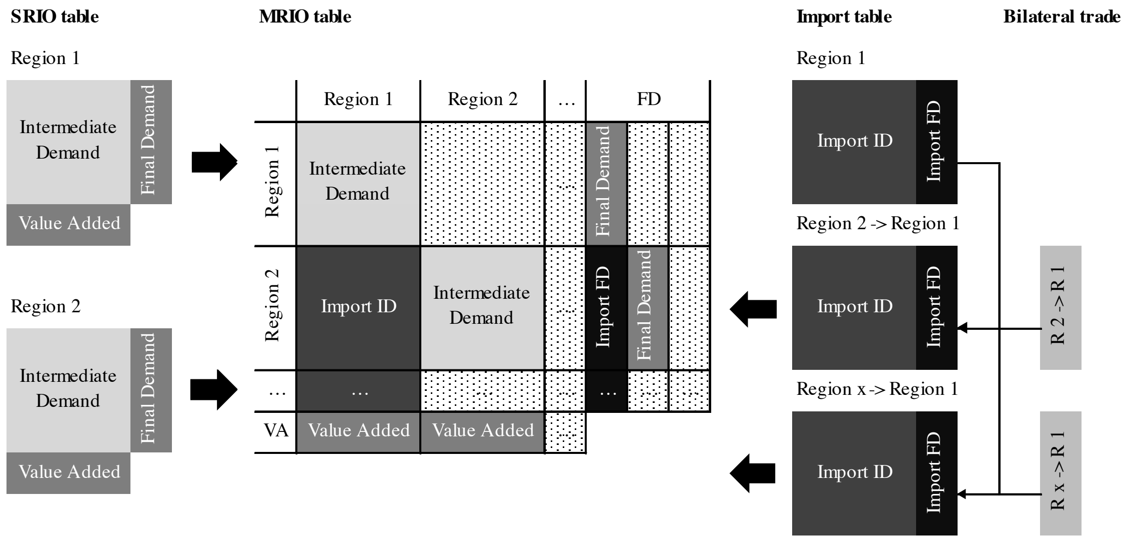

Fig. 1.3: Construction process of MRIO table with non-survey method; the MRIO table is constructed from SRIO tables, import tables, and bilateral trade data. SRIO tables are aligned as diagonal domestic blocks and value added blocks in the MRIO table (see left side). In the non-survey method, intermediate demand (ID) and final demand (FD) in import tables are disaggregated into bilateral import tables using bilateral trade data (region (R) x -> region (R) 1) (see right side).

1.1.1. MRIO or IRIO

There is a lack of consensus about the terminology for multi-/inter-national input-output modelling: should MRIO or IRIO be used as the correct term for this type of model? According to definitions from the literature, IRIO (inter-regional input-output) tables have 'perfect' trade matrices based on real information gained from surveying industries, whereas MRIO tables have derived trade matrices based on trade coefficients (as described above), because they do not conduct surveys and therefore have incomplete information (Guo, Webb, & Yamano, 2009).

Both, IRIO and MRIO are aiming at a structure where bilateral trade is separated by industry; that is, both aim to understand what a country imports, what kind of goods are imported, and who or which industry uses these goods. However the means to achieve this aim may be different. Some researchers go beyond the trade coefficient (non-survey) approach for compiling MRIOs by incorporating superior data, e.g. industry-specific import reports (Fig. 1.4). The aim is to approximate IRIO data.

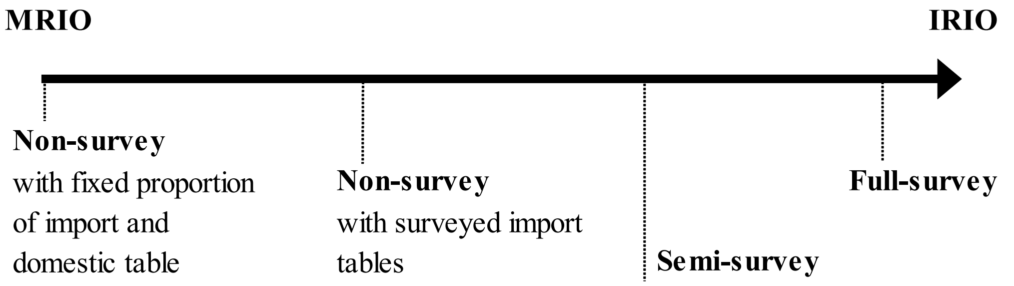

Fig. 1.4: Transition between MRIO and IRIO; as we use or survey actual international trade blocks, the expression changes. MRIO starts with the non-survey method with a fixed proportion of import and domestic tables. The expression of MRIO is gradually changed to IRIO if we use surveyed import tables and surveyed international trade blocks. Once we have surveyed all international trade blocks, then we call the table an IRIO table.

This means that whether a table is IRIO or MRIO is a matter of quality as well as of structure, and it is not clear what minimum level of quality or real data is required before an MRIO table can be labelled IRIO. Adopting quality as a criterion in the definition makes it subjective and is potentially misleading. Strictly speaking, IO tables comprising several nations and international trade data will always be MRIO tables because the information necessary for a true IRIO table is not likely to become available in the foreseeable future. Therefore, it is suggested that the term IRIO should only be used if a clear and significant superiority of data quality compared to MRIO tables can be demonstrated. In this chapter, and also throughout the book, the term 'MRIO' is used to denote the entire continuum.

1.1.2. History

Since Isard (1951) proposed the initial framework of MRIO tables, there has been a long history of MRIO analysis. In the beginning stage, researchers tried to find a more sophisticated form of MRIO table for the new world economic framework. Although MRIO analysis is out of the mainstream of macroeconomics, MRIO has been one of the favorable tools for regional science (Hewings & Jensen, 1987). The development of regional science has facilitated compilation of regional input-output tables such as in China and Japan and clarified structural change and regional interdependence. Recently MRIO frameworks have attracted lots of attention from researchers in the field of environmental issues (Wiedmann, 2009). The growth in international trade has made researchers in other fields besides environmental problems realize the usefulness of MRIO tables. For example, there is a slight interest growing in value added trade (Foster, Stehrer, & de Vries, 2011; Johnson & Noguera, 2012; Koopman, Powers, Wang, & Wei, 2011). Traditional trade volume from developing to developed countries grows rapidly, but people tend to think that developing countries don't add a lot of value because their main role is assembling. Recent studies have found that the MRIO table is a useful way to estimate which country and sector add actual value, i.e., value added trade (e.g. Trefler & Zhu, 2010).

1.2. MRIO benefits and limitations

MRIO analysis is becoming a powerful tool to analyze environmental problems because there are no alternatives to analyze the complex global supply chain. Here we introduce three benefits, coverage, extension, and application capacities; and two limitations, sector detail and time lag compared to other environmental system analytical tools like top-down LCA.

1.2.1. Benefits

The first benefit of MRIO is geographical and supply chain coverage. MRIO tables cover the whole economic structure of multi-region and export and import within and outside these regions and finite stage of supply chain theoretically. Therefore, in MRIO analysis, we can avoid arbitrary geographical and production stage boundary settings that we have to be concerned with when using bottom-up LCA and footprinting.

The second beneficial feature of MRIO is that we can easily apply MRIO analysis to any company. For example, despite the growing interest in carbon footprints of products (CFP), estimation of CFP is hard work for most companies because usually companies need to trace their long supply chain of many products. MRIO can play the role of tracer of products, so we only need to prepare direct carbon emissions by sector other than MRIO table to estimate CFP. In addition to tracer role, we have opportunities to use MRIO results as a screening and complementary role with existing bottom-up LCA results (Huang, Lenzen, Weber, Murray, & Matthews, 2009; Suh & Huppes, 2002).

The final benefit of MRIO analysis is application capacities. MRIO isn't the special but same framework as SRIO, so we can use many techniques that we have used in SRIO analysis such as structural path analysis (SPA) (Peters & Hertwich, 2006) and structural decomposition analysis (SDA) (Baiocchi & Minx, 2010). Structural path analysis (SPA) traces the supply chains of production processes, so we can find, for example, the path Australian iron ore mining sector → Thailand automobile manufacturing sector → Japanese automobile household consumption sector using SPA. SDA is a technique to find the driving factors behind changes in emissions over time. SDA can distinguish driving factors (e.g.

emission intensities, intermediate input structure, final demand structure, and final demand level).

1.2.2. Limitations

One of the biggest reasons why input-output analysis isn't widely used for product LCA is sector detail. Because of low sector resolution, input-output analysis sometimes can't distinguish the important differences of products or industries. One region sometimes provides different sector classification tables from another region, so most of MRIO studies aggregate input-output tables into one common classification. That process looses lots of information and makes product LCA more difficult. One solution against this limitation is a hybrid-LCA approach. A hybrid approach integrates the sector- (input-output approach) and process-based (bottom-up LCA approach) data (Suh et al., 2004). However, no one has yet integrated a MRIO table and process-based data as far as we know.

The other limitation of MRIO is time lag. Benchmark input-output tables are usually published every 5 years and released a few years later because compilation of these tables needs a lot of data and labor. Of course some countries publish annual input-output tables such as Japan and USA, but these tables are aggregated or simplified based on benchmark input-output tables. Because the MRIO table is an assembly of SRIO tables, differences in the publication year of SRIO tables affects the quality of the MRIO. The emissions embodied in bilateral trade (EEBT) method (see chapter 2 for the detail) may be able to overcome the limitation because international trade is updated quickly unlike input-output tables.

Though there are MRIO features that we can't introduce in this section, following sections of this thesis clarify benefits and limitations and provide examples of MRIO.

Reprinted from Kanemoto, K., Murray, J. (2013). What is MRIO: Strengths and Limitations" In: Joy Murray and Manfred Lenzen (Eds.), The Sustainability Practitioner's Guide to Multi-Regional Input-Output Analysis, Common Ground Publishing, Illinois, USA.

2. Frameworks for comparing emissions associated with production, consumption, and international trade

2.1. Introduction

During the past few years, there has been an increasing number of contributions to the international literature about the measurement of carbon emissions embodied in international trade (Hertwich & Peters, 2009; Nansai et al., 2009; Zhou & Kojima, 2009), about the ensuing issue of carbon leakage (Lenzen, Pade, & Munksgaard, 2004; Peters & Hertwich, 2008a; Peters, Minx, et al., 2011; Peters, 2010a; Wiedmann, Lenzen, Turner, & Barrett, 2007; Wiedmann, 2009), and more generally about the principles of producer, consumer, and shared responsibility (R. Andrew & Forgie, 2008; Lenzen, Murray, Sack, & Wiedmann, 2007; Lenzen & Murray, 2010; Munksgaard & Pedersen, 2001; Rodrigues & Domingos, 2008), and their policy implementation (Minx et al., 2009; Peters & Hertwich, 2008a; Peters, 2010b; Peters et al., 2009; Wiedmann, 2009; Wiedmann et al., 2010). For policy to reorient itself from its current focus on territorial emissions to any kind of consumer-responsibility metric, definitions and principles of embodied-emissions accounting must be transparent and unambiguous. This is particularly true for country comparisons and trade balances, since these are possible policy measures for determining the allocation of financial burdens across countries. At present, there are inconsistencies in the definition and application of trade balances and emissions comparisons (Peters & Solli, 2010), and a harmonization of understandings and standardization of concepts is needed to enhance the credibility and robustness of estimates for emissions embodied in international trade.

Estimates of consumption-based emission inventories (carbon footprints) and emissions from the production of internationally traded produces require a method to accurately enumerate the global supply chain. Given the complexity of international trade routes, Environmentally Extended Multi-Regional Input-Output (EE- MRIO) analysis has emerged as the favored method for quantifying emission embodiments (Wiedmann et al., 2007; Wiedmann, 2009). Input-Output Analysis (IOA) is a method specifically designed to analyze the relationship between economic sectors and hence enumerate the supply chain (Leontief, 1936, 1966). Multi- regional IOA was developed early (Isard, 1951; Leontief, 1953) and a range of MRIO approaches exist (Oosterhaven, 1984). Environmental extensions were developed independently around 1970 (Ayres & Kneese, 1969; Leontief, 1970). The analysis of global environmental problems with EE-MRIO has been arguably the fastest growing area of IOA and a range of studies now exist (Wiedmann et al., 2007; Wiedmann, 2009). Strengths and weaknesses of the MRIO approach were scrutinized for government review in the European EIPOT project (Wiedmann, Wilting, Lenzen, Lutter, & Palm, 2011). In addition, the theoretical framework of MRIO can be used to represent other methods – such as Life Cycle Assessment or hybrid approaches - for estimating embodied emissions (Heijungs & Suh, 2002; Peters & Solli, 2010). Thus, theoretical developments in MRIO can often be applied directly to other related fields.

In this article, we use MRIO as a basis to critically examine a number of emissions accounting concepts such as variants of territorial emissions reported to statistical bodies, carbon footprints, and emissions embodied in bilateral trade (EEBT). In particular, we present a number of trade balance concepts for emissions and assess whether they are compatible and consistent with concepts used for monetary trade balances. Our aim is to ensure that consistent definitions are used in studies to allow comparability and to avoid confusion for researchers, policy makers, and the interested public. The following Section reviews accounting identities for multi-region and single-region cases. Section 2.3 extends monetary accounting identities to embodied "emissions". Rather than focusing on emissions alone, we consider "factor use" more generally to show that the concept of embodiment in trade is also applicable to other quantities such as energy, land, water, or labor. In Section 2.4 we make our central arguments by analyzing the advantages and shortcomings of various concepts. Section 2.5 concludes by highlighting implications for policy, in particular the need for standardization of concepts and definitions.

2.2. Accounting Identities

Let r and s denote the region (for example country) origin and destination of MRIO transactions. In an MRIO, the sector- and region-wise balance of gross output x holds (subject to correct inclusion of taxes less subsidies on products as a row in value added v):

$$x^r_{in,i} = x^r_{out,i} \Leftrightarrow \sum_{ks} v^{sr}_{ki} + \sum_{js} T^{sr}_{ji} = \sum_{js} T^{rs}_{ij} + \sum_{ls} y^{rs}_{il} \quad \forall i, r, \tag{1}$$

where T is intermediate demand, y is final demand, and v is value added. In our notation T^{rs}_{ij} clearly states that sector i operates in region r and sector j in region s, so we will not write $i^{(r)}$, $j^{(s)}$, etc. In MRIO the final demand, y, contains l categories: household and government final consumption, gross fixed capital expenditure, and changes in inventories. Value added, v, contains k components: compensation of employees, taxes less subsidies on production, and gross operating surplus. Imports to final consumption are included in y, but imports to industry are included in T. Similarly, exports to industry appear in T, and exports into final consumption appear in y. Whilst in single-region input-output (SRIO) tables all exports are part of final demand.

When summing over r and i, we find that $\sum_{rijs} T^{sr}_{ji} = \sum_{rijs} T^{rs}_{ij}$ (Fig. 2.1), and produce the Global Accounting Identity

$$\begin{aligned} & \sum_{riks} v^{sr}_{ki} = \sum_{rils} y^{rs}_{il} \\ \Leftrightarrow\ & \sum_{rik} v^{rr}_{ki} + \sum_{riks \neq r} v^{sr}_{ki} = \sum_{ril} y^{rr}_{il} + \sum_{rils \neq r} y^{rs}_{il} \\ \Leftrightarrow\ & \sum_r GDP^r + \sum_r PRIMIMP^r = \sum_r GNE^r + \sum_r FINEXP^r \ , \end{aligned} \tag{2}$$

which sums Gross Domestic Product (GDP), Gross National Expenditure (GNE), imports of primary inputs (*PRIMIMP*) and exports into final demand (*FINEXP*) over all trade partners r. Usually, international trade $PRIMIMP^r = \sum_{riks \neq r} v_{ki}^{sr}$ in primary inputs v_{ki}^{sr} is zero but is included here for the sake of theoretical completeness. Since we include taxes less subsidies on products in our value-added block, $\sum_{rik} v_{ki}^{rr}$ is valued at market price, and therefore coincides with the definition of GDP in the input-output table handbook (United Nations, 1999). Note once again that exports here only include exports to final, and not intermediate, consumption.

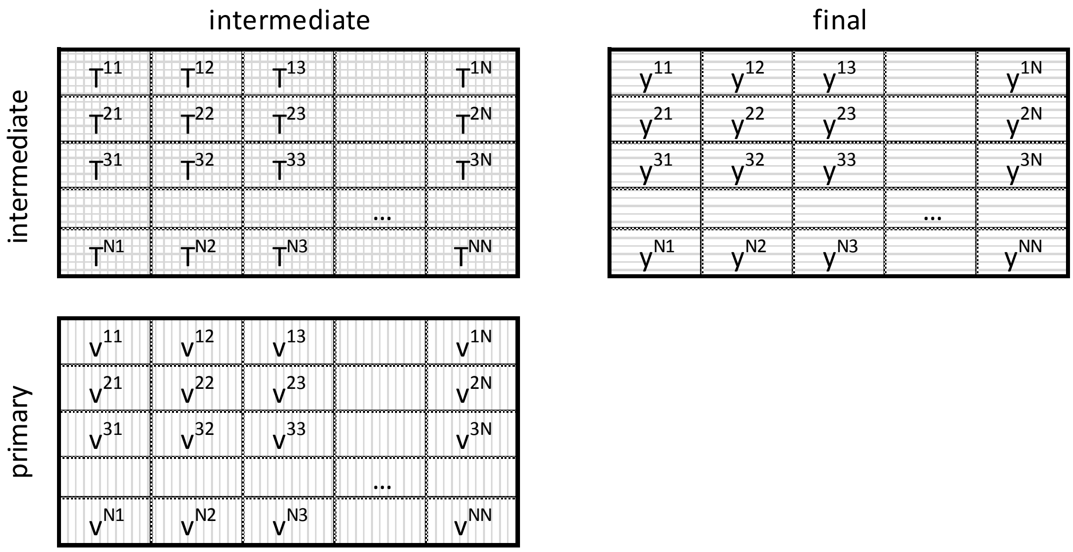

Fig. 2.1: Global Accounting Balance in an MRIO. Vertically hatched: sums of sectoral inputs, must equal horizontally hatched: sums of sectoral outputs. Note that block descriptors are given with sector indices, for example, T^{32} is a matrix with elements T_{ij}^{32}. Note also that the entire intermediate demand block T

including intermediate trade $T_{ji}^{s,r\neq s}$ cancels out (see Eq. 2).

The region-wise single-region balances read

$$\sum_{ks} v_{ki}^{sr} + \sum_{js} T_{ji}^{sr} = \sum_{js} T_{ij}^{rs} + \sum_{ls} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow \sum_{k} v_{ki}^{rr} + \sum_{ks\neq r} v_{ki}^{sr} + \sum_{j} T_{ji}^{rr} + \sum_{js\neq r} T_{ji}^{sr}$$

$$= \sum_{j} T_{ij}^{rr} + \sum_{js\neq r} T_{ij}^{rs} + \sum_{l} y_{il}^{rr} + \sum_{ls\neq r} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow \sum_{k} v_{ki}^{rr} + \sum_{ks\neq r} v_{ki}^{sr} + \sum_{js\neq r} T_{ji}^{sr} = \sum_{js\neq r} T_{ij}^{rs} + \sum_{l} y_{il}^{rr} + \sum_{ls\neq r} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow VA_i^r + PRIMIMP_i^r + INTIMP_i^r = INTEXP_i^r + FD_i^r + FINEXP_i^r \quad \forall i,r. \qquad (3)$$

Summing Eq. 3 over i yields a balance of r-region Gross Domestic Product (*GDP*), imports of primary (*PRIMIMP*) and intermediate (*INTIMP*) imports, with r-region Gross National Expenditure (*GNE*), and intermediate (*INTEXP*) and final (*FINEXP*) exports.

$$GDP^r + PRIMIMP^r + INTIMP^r = GNE^r + INTEXP^r + FINEXP^r \quad \forall r. \qquad (4)$$

It follows that the National Accounting Identities for countries r can be reproduced by including all imports and exports, a part of which is included as intermediate transactions because of the endogenization of intermediate trade in an MRIO.

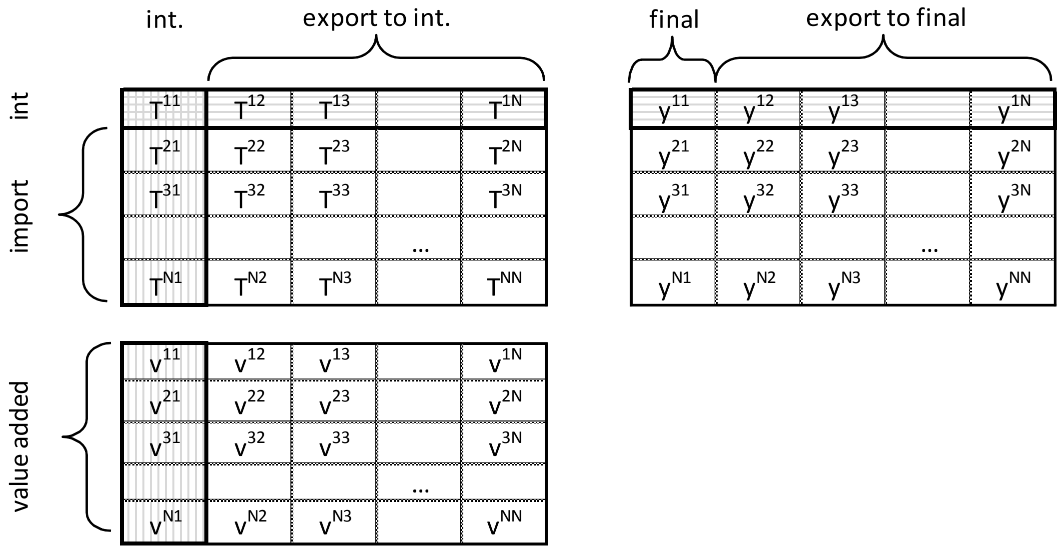

Fig. 2.2: National Accounting Balance in an MRIO (exemplary for region 1). Vertically hatched: sums of sectoral inputs, must equal horizontally hatched: sums of sectoral outputs. Note that only the intra-region intermediate (int) demand block T^{11} cancels out (see Eq. 3). In MRIO exports are separated into exports to intermediate (int) and final consumption (as shown).

2.3. Factor requirements, inventories and footprints

Generalizing Eq. 1 to exogenous factor inputs F (for example greenhouse gas emissions in units of tonnes CO_2-e, energy use in Joules, land use in hectares, water use in liters, labor in employment-years, etc) leads to

$$x^r_{out,i} = \sum_{js} T^{rs}_{ij} + \sum_{ls} y^{rs}_{il} \quad \forall i, r$$

$$\Leftrightarrow \mathbf{x} = \mathbf{T}\mathbf{1}^{\mathrm{T}} + \mathbf{y}\mathbf{1}^{\mathrm{y}} = \mathbf{A}\mathbf{x} + \mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Leftrightarrow (\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Rightarrow F = \mathbf{f}\mathbf{x} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}} = \sum_{irjst} f_i^r L_{ij}^{rs} \sum_k y_{jk}^{st} \ , \qquad (5)$$

where $\mathbf{1}^{\mathrm{y}} = \{1,1,\cdots,1\}$ is a suitable aggregation operator for summing total final demand, the $f_i^r = F_i^r / x_i^r$ are called factor intensities, and where the factor input in each region and sector F_i^r is calculated according to the same system boundary as the economic output x_i^r.

The production-based account for each region is defined as $\sum_i F_i^r$. Additionally summing over all *r*, the variable *F* in Eq. 5 describes the entire factor content of the world economy. In general, IO data is consistent with the System of National Accounts (European Comission, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank, 2009) and when extended to environmental impacts leads to the National Accounts Matrix with Environmental Accounts (NAMEA) (European Comission, 2001; United Nations, European Comission, International Monetary Fund, Organization for Economic Co-operation and Development, & World Bank, 2003), or the equivalent for factor use. NAMEAs have a different system boundary to territorial-based accounts, for example, as in greenhouse gas emissions reported to the UNFCCC (IPCC, 2006). The main difference is that the territorial- based accounts do not include international transportation and do not allocate tourist activities to the location of residency, both of which can be significant for some countries (Pedersen & de Haan, 2003; Peters & Hertwich, 2008a; Peters et al., 2009). In the following, we only use production-based accounts.

Due to the linearity assumption in IOA, once the variables f, A, and L have been defined as in Eq. 5, it is possible to repeat the analysis for final demands of arbitrary size.

$$\bar{F} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\bar{\mathbf{y}}\mathbf{1}^{\mathrm{y}} = \sum_{irjst} f_i^r L_{ij}^{rs} \sum_k \bar{y}_{jk}^{st}, \tag{6}$$

where $\bar{y}$ is an arbitrary final demand and f and A are defined from the total demand and output in Eq. 5. Arbitrary final demands are often used in input-output-based life-cycle studies, where $\bar{y}$ may hold monetary data for example on household consumption or wind turbines. In the case of $\bar{y}$ holding some arbitrary final demand, $\bar{F}$ would represent the emissions caused by this demand, for example the construction of a wind turbine. Below we investigate a number of ways for F to be broken down into components. In this respect, we use terms such as "factor inventory" and "footprint" in both the national and arbitrary context, however the reader may note that these terms have a restricted, specific meaning when describing emissions inventories reported to the UNFCCC (IPCC, 2006), life-cycle inventories as defined by the ISO (ISO, 1998), or carbon footprints (Wiedmann & Minx, 2007).

The factor uses F in Eq. 5 can be allocated in many ways, by grouping the summation indices. Since there are 5 indices, there are potentially $5 \times 4 = 20$ ways of slicing F into 2-index components. For example, such slices could reflect the commodity-region pairs i-r (superscript (f); place of factor origin), j-s (superscript (p); place of last sale), and j-t (superscript (c); place of final destination, consistent with footprint concept). There are also $5 \times 4 \times 3 = 60$ ways of slicing F into 3-index components. Of course, not all of these breakdowns make intuitive sense. Below, we will present a selection of allocations, consistently retaining index r for the emitting region, s for the last selling region, and t for the consuming region.

In the case of the final destination allocation, the resulting components are factor footprints of commodities j consumed in countries t (or consumption-based inventory according to (Peters, 2008)). The world's factor inventory decomposes into

$$F = \sum_{jt} F_j^{(\mathrm{c})t} = \sum_{jt} \sum_{irs} f_i^r L_{ij}^{rs} y_j^{st}. \tag{7}$$

The total factor footprint of region t is then

$$\Leftrightarrow F^{(\mathrm{c})t} = \sum_{ijrs} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall t. \tag{8}$$

$F^{(\mathrm{c})t}$ describes the factors embodied in consumption, and at the sector level the factors can be allocated for example to the commodity j consumed in region t:

$$F = \sum_{jt} F_j^{(\mathrm{c})t} = \sum_{jt} \left\{ \sum_{rs} \mathbf{f}^r \, \mathbf{L}^{rs} \hat{\mathbf{y}}^{st} \right\}_j^t \Rightarrow F_j^{(\mathrm{c})t} = \sum_{irs} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j,t \tag{9}$$

which reveals the embodied factor use allocated to each consumed commodity j, for example, the total factors allocated to food consumption. Second, the factors can be allocated to where the emissions embodied in the commodities consumed in region t occur:

$$F = \sum_{jrt} F_j^{(\mathrm{c})rt} = \sum_{jrt} \left\{ \sum_s \hat{\mathbf{f}}^r \, \mathbf{L}^{rs} \mathbf{y}^{st} \right\}_j^{rt} \Rightarrow F_j^{(\mathrm{c})rt} = \sum_{is} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j,r,t \tag{10}$$

which reveals, for example, the countries and sectors using factors to support consumption in region t.

In the case of place of last sale allocation, the components are MRIO sales-based emissions embodied in commodities j finally sold by countries s (according to (Peters, 2008))

$$F = \sum_{js} F_j^{(\mathrm{p})s} = \sum_{js} \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st}$$

$$\Leftrightarrow F^{(\mathrm{p})s} = \sum_{ijrt} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall s. \tag{11}$$

Since $F^{(p)s}$ describes factors embodied in sales, it make sense to define

$$F = \sum_{js} F_j^{(\mathrm{p})s} = \sum_{js} \left\{ \sum_{irt} \mathbf{f}^r \, \mathbf{L}^{rs} \hat{\mathbf{y}}^{st} \right\}_j^s \Rightarrow F_j^{(\mathrm{p})s} = \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, s \tag{12}$$

where $F_j^{(p)s}$ are the emissions embodied in the sold commodity j. It may also be of interest to look further at where the emissions embodied in commodities sold from region s occur:

$$F = \sum_{jrs} F_j^{(\mathrm{p})rs} = \sum_{jrs} \left\{ \sum_t \hat{\mathbf{f}}^r \, \mathbf{L}^{rs} \mathbf{y}^{st} \right\}_j^{rs} \Rightarrow F_j^{(\mathrm{p})rs} = \sum_{it} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, r, s. \tag{13}$$

In the case of factor origin allocation, the components replicate the production-based inventories of producing sectors i in countries r,

$$F = \sum_{ir} F_i^{(\mathrm{f})r} = \sum_{ir} f_i^r \sum_{jst} L_{ij}^{rs} y_j^{st}$$

$$\Leftrightarrow F^{(\mathrm{f})r} = \sum_{ijst} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall r. \tag{14}$$

Since $F^{(\mathrm{f})r}$ describes emissions from production, it make sense to define

$$F_i^{(\mathrm{f})r} = f_i^r \sum_{jst} L_{ij}^{rs} y_j^{st} \quad \forall i, r \tag{15}$$

where $F_i^{(\mathrm{f})r}$ are the emissions caused during the production of commodity i.

Note that the inventories in Eq. 8 and 11 contain factor uses that are spread across the entire world. Only production-based inventories feature emissions originating only from one region.

The terms we have used for total factor footprint Eq. 8, 11, and 14 are not universally applied and many authors have used their own terminology. The terminology can relate to the final consumption under investigation (such as a factor footprint) and also the method of allocating that final consumption (such as allocating a factor footprint to the sectors where the emissions occur, see (Peters, 2008)). The terminology associated with the factor footprint is arguably the only term that has not been used in multiple ways. Production-based inventories most generally refer to a NAMEA, but this is often used interchangeably with territorial-based inventories even though the terms are different (see above, and the discussions in (Peters & Hertwich, 2008a)). Most confusing would perhaps be the use of "production-based inventory" in an MRIO context, Eq. 11, as this form of "production" is not obvious to most analysts (see (Peters, 2008)). We use the term "sales-based inventory" to clearly differentiate the concept. A sales-based inventory includes factor use to produce products for final consumption, and thus intermediate consumption is included indirectly in the calculation. A sales-based inventory and consumption-based inventory only really differ in which country gets allocated the emissions. For example, the emissions to produce y^{rs} can be allocated to the consumer s (consumption-based) or to the producer r (sales-based). To a non-IO analyst the sales-based inventory could be seen as unusual as it only treats final consumption, thus, the exports from a country only include products for final consumption and not intermediate consumption. For example, if a seemingly identical car is exported from a country and consumed by industry (intermediate consumption) for further processing then it is not included directly in a sales based inventory (but indirectly in the production of another product). Thus, in the hypothetical case that Japan sold all its cars to industry, Japan would be allocated zero emissions in a sales- based inventory of cars (see (Gallego & Lenzen, 2005; Lenzen et al., 2007) for an approach to overcome this counter-intuitive results). While our terminology may not be preferred by some analysts, it should be made apparent that a clear definition and description of different terms is needed to avoid confusion within and across studies.

2.4. Trade balances and comparisons

There are different ways to compare the emissions associated with production, consumption, and international trade. Comparisons often lead to the consideration of the difference between production and consumption, with the difference interpreted as a "trade balance" in factor use. While this trade balance draws analogies to a monetary trade balance, the relationship may only be weak (Peters, 2008). For consistency, we argue that a "factor trade balance" should have the following properties: symmetry (exports measured at the country of origin are the same as imports measured at the country of destination) and zero sum at the global level (the sum over all trade balances in the world is zero). These properties are desirable because they preclude any discrepancies or unallocated factor uses.

2.4.1. Footprint versus production

A factor comparison that is often used in the literature (for example (Atkinson, Hamilton, Ruta, & van der Mensbrugghe, 2011; Peters & Solli, 2010; Serrano & Dietzenbacher, 2010; Wiedmann et al., 2010)) is the difference between territorial inventories and footprints (Eq. 15 and 9)

$$F_j^{(\mathrm{f})s} - F_j^{(\mathrm{c})s} = f_j^s \sum_{irt} L_{ji}^{sr} y_i^{rt} - \sum_{irt} f_i^r L_{ij}^{rt} y_j^{ts}. \tag{16}$$

This comparison retains international factor inputs (supply chains) $\sum_{ir} f_i^r L_{ij}^{rs} y_j^{ss}$ for domestically produced final demand y_j^{ss}, and domestic factor inputs (supply chains) $f_j^s \sum_{irt} L_{ji}^{sr} y_i^{rr}$ for domestically produced final demand y_i^{rr}.[1]

A drawback is that Eq. 16 is not further reducible, and is also not symmetrical. It also does not fulfill the commodity-wise zero-sum condition for trade balances $\sum_s \left(F_j^{(\mathrm{f})s} - F_j^{(\mathrm{c})s}\right) = 0 \; \forall j$, which can be shown by summing Eq. 16 over s, and re-indexing $r \rightarrow s$, $t \rightarrow r$, and $s \rightarrow t$ in the second summand, which results in $\sum_{sirt} f_j^s L_{ji}^{sr} y_i^{rt} - \sum_{sirt} f_i^r L_{ij}^{rt} y_j^{ts} = \sum_{sirt} f_j^s L_{ji}^{sr} y_i^{rt} - \sum_{sirt} f_i^s L_{ij}^{sr} y_j^{rt} \neq 0 \; \forall j$. In

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[1] Note that in Eq. 16, and also in Eqs. 17 and following, we use L_{ij}^{rs} and L_{ij}^{rt}, and y_j^{st} and y_j^{ts}, and thus assume that the input-output tables of countries *s* and *t* are classified according to the same set of sectors $\mathbb{J} = \{j\}$. We retain this assumption throughout this article for the sake of clarity and readability when putting forth our arguments. However, we recognize that in all generality, $\mathbb{J}^s \neq \mathbb{J}^t$ and $j^{(s)} \neq j^{(t)}$, and strictly speaking Eq. 16 for example should be replaced by

$$F_{j(s)}^{(\mathrm{p})s} - F_{j(s)}^{(\mathrm{c})s} = \sum_{ir,t\neq s} f_i^r \left(L_{ij(s)}^{rs} y_{j(s)}^{st} - L_{ij(t)}^{rt} y_{j(t)}^{ts} C_{j(t)j(s)}^{ts} \right),$$

where $C_{j(t)j(s)}^{ts}$ is a normalised concordance matrix translating any $\mathbb{J}^t$-classified vector into a $\mathbb{J}^s$-classified vector.

essence, this is because the territorial and footprint measures cover - in part - geographically non-overlapping factor uses: Whilst the territorial inventory is restricted to domestic factor uses only, any footprint extends to all countries in the world. Hence, the balance in Eq. 16 should not be called an emissions trade balance, because it is not compatible with monetary trade balances. However, the comparison in Eq. 16 does fulfill a zero-sum condition for the global trade balance $\sum_{js}\left(F_j^{(\mathrm{f})s}-F_j^{(\mathrm{c})s}\right)=0$.

2.4.2. MRIO-based trade balance

Many analysts have presented a factor use "trade balance" which is meant to give an indication of the magnitude in the factors embodied in exports compared to the factors embodied in imports. In an MRIO setting, what to include as factors embodied in trade is not obvious as some trade is for intermediate and some for final consumption. Using our consumption- and sales-based inventories, it is possible to define an MRIO factor use trade balance as the difference between consumption and production (as measure by the sales-based inventory). Peters (2008) interprets that the difference $F_j^{(p)t}-F_j^{(c)t}$ represent a well-defined trade balance as "it is a balance of trade in final consumption", but we find that a more appropriate interpretation is

$$\begin{aligned} F_j^{(\mathrm{p})s}-F_j^{(\mathrm{c})s} &= \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st} - \sum_{irt} f_i^r L_{ij}^{rt} y_j^{ts} \\ &= \sum_{ir,t\neq s} f_i^r \left(L_{ij}^{rs} y_j^{st} - L_{ij}^{rt} y_j^{ts}\right), \end{aligned} \tag{17}$$

where the term $L_{ij}^{rs} y_j^{st} - L_{ij}^{rt} y_j^{ts}$ represents the balance of *gross output requirements* for imports $L_{ij}^{rt} y_j^{ts}$ from all other countries $t \neq s$ for final demand in region *s*, and exports $L_{ij}^{rs} y_j^{st}$ from region *s* for final demand in all other countries $t \neq s$. This is because the terms for $s = t$ cancel out, and hence domestically produced final demand – including its domestic and international gross output and factor requirements – do not play a role in this equation.

The sales-based inventory appears somewhat unintuitive and includes global and not domestic emissions. This is because it only includes emissions to produce and export products for final consumption representing the point of final sale of a product to a final consumer and not an intermediate consumer; exports to intermediate consumption are treated endogenously in the MRIOT. Including exports to intermediate consumers in a sales- based inventory would cause double counting of emissions. The necessity for the definition used in Eq. 8 becomes clear when deriving the national accounting balance (production = consumption - imports + exports) of factor uses that corresponds to Eq. 11. This balance reads

$$\underbrace{F_j^{(\mathrm{p})s}}_{\text{production}} = \sum_r f_i^r \left[\underbrace{\sum_{it} L_{ij}^{rt} y_j^{ts}}_{\text{consumption}} - \underbrace{\sum_{it \neq s} L_{ij}^{rt} y_j^{ts}}_{\text{imports}} + \underbrace{\sum_{it \neq s} L_{ij}^{rs} y_j^{st}}_{\text{exports}} \right]$$

$$= \sum_r f_i^r \left[\sum_i L_{ij}^{rs} y_j^{ss} + \sum_{it \neq s} L_{ij}^{rs} y_j^{st} \right] = \sum_r f_i^r \sum_{it} L_{ij}^{rs} y_j^{st} \qquad (18)$$

where "exports" cover the factor use in region *r* required to produce final goods in *s,* which are then sold by *s* to *t,* and "imports" cover factor use in region *r* required to produce final goods in *t* which are then sold by *t* to *s.* Serrano & Dietzenbacher (2010) produce a similar balance in comparing "production – consumption" with "exports – imports".

The MRIO factor trade balance only directly considers trade destined for final consumption because trade in intermediate consumption considered endogenously. Therefore, exports or imports into intermediate consumption for a region do not appear in its trade balance. For example, an exporter of crude petroleum will not have crude petroleum in their trade balance as this crude oil is an intermediate good processed to refined petroleum for use as a final good. The degree to which this will affect the trade balance of individual countries will depend on the magnitude of trade into intermediate and final consumption. For many countries, international trade directly for final demand represents a minor portion of total final demand (on average about 10%, see Fig. 2.3a), and also of total trade (on average about 35%, see Fig. 2.3b); however, for some countries this proportion is higher and at the sector level it can vary from 0-100% depending on the product. As a consequence, the trade balance proposed in Eq. 15 would generally operate only on a minor segment of bilateral trade between countries s and t, and characterize only a small portion of the countries' consumption. An additional aspect, is that the production-based inventory and the trade balance both include emissions from other countries which may make interpretations difficult and contrived (Peters, 2008). As a result, whilst Eq. 17 leads to a nice symmetrical relationship, and also satisfies that the sum of all trade balances $\sum_s \left(F_j^{(\mathrm{p})s} - F_j^{(\mathrm{c})s} \right) = 0$ for all commodities j, it may not be a useful or policy relevant quantity.

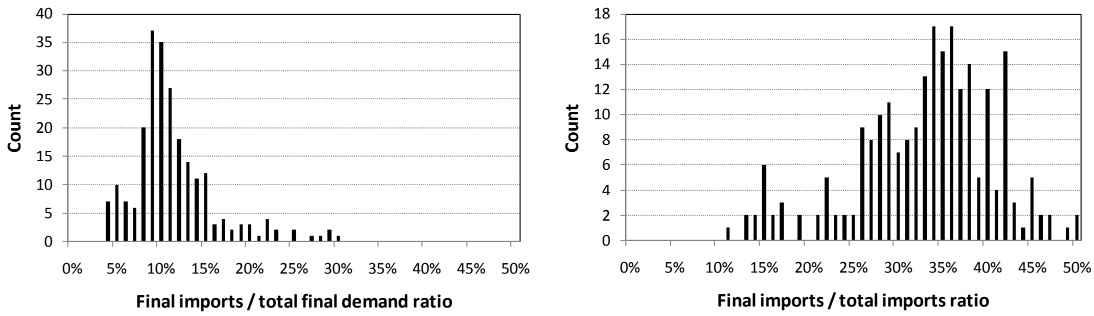

Fig. 2.3: a) Frequency count of the final imports / total final demand ratio; b) frequency count of the final imports / total imports ratio. Compiled based on national input-output tables of Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, UK, Greece, Hong Kong, Hungary, Indonesia, India, Ireland, Israel, Italy, Japan, Korea, Lithuania, Latvia, Mexico, Macedonia, Malaysia, Netherlands, Norway, New Zealand, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, Sweden, Thailand, Turkey, Taiwan, USA, and South Africa, dated between 1990 and 2007.

2.4.3. EEBT trade balance

Some authors suggest using the Emissions Embodied in Bilateral Trade (EEBT) method, which can be evaluated using multiple single-region input-output models (Peters & Hertwich, 2008b; Peters, 2008; Weber & Matthews, 2007; Wiedmann, 2009; Zhou, Liu, & Kojima, 2010). In contrast to the MRIO approach, the EEBT method considers domestic supply chains but exogenously include both trade in intermediate and consumption products. The EEBT method compares inventories for production $EEBT_j^{(\mathrm{p})s}$ and consumption $EEBT_j^{(\mathrm{c})s}$ (Peters, 2008),

$$EEBT_j^{(\mathrm{p})s} = \sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^s L_{ij}^{ss} (\sum_k T_{jk}^{sr} + y_j^{sr}) \,, \tag{19}$$

$$EEBT_j^{(\mathrm{c})s} = \sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^r L_{ik}^{rr} \left(\sum_k T_{kj}^{rs} + y_j^{rs}\right) \,. \tag{20}$$

and the trade balance is given by the difference

$$B_j^{(EEBT)s} = EEBT_j^{(p)s} - EEBT_j^{(c)s} \tag{21}$$

$$B_j^{(EEBT)s} = \sum_{i,r\neq s} f_i^s L_{ij}^{ss} (\sum_k T_{jk}^{sr} + y_j^{sr}) - \sum_{i,r\neq s} f_i^r L_{ik}^{rr} \left(\sum_k T_{kj}^{rs} + y_j^{rs}\right). \tag{22}$$

where the domestic components cancel out. This trade balance, consequently, is framed in terms of a difference in total exports and imports in the same context as a monetary trade balance. The rationale behind this approach is that it exogenously includes all imports and exports, and thus EEBT correlates with bilateral trade data with the emission intensity as the correlation coefficient. In contrast, the MRIO only exogenously includes imports and exports of final consumption, and does not correlate with bilateral trade data. Since this method only includes domestic (*rr*- and *ss*-) supply chains, it has the drawback of excluding factor uses embodied in imports required for exports (R. Andrew, Lennox, & Peters, 2010). This formulation is symmetrical, and also fulfills the zero-sum trade-balance condition $\sum_s\left(EEBT_j^{(\mathrm{p})s} - EEBT_j^{(\mathrm{c})s}\right) = 0 \;\forall j$, because

$$\sum_s EEBT_j^{(\mathrm{p})s} - \sum_s EEBT_j^{(\mathrm{c})s}$$
$$= \sum_s \left(\sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^s L_{ij}^{ss} \left(\sum_k T_{jk}^{sr} + y_j^{sr}\right)\right)$$

$$-\sum_s\left(\sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right)\right)$$

$$= \sum_{i,r\neq s,s} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_{i,r\neq s,s} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right)$$

$$= \left\{\sum_{irs} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_i f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{ss} + y_j^{ss}\right)\right\}$$

$$-\left\{\sum_{irs} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right) - \sum_i f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{ss} + y_j^{ss}\right)\right\}$$

$$= \sum_{irs} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_{irs} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right) = 0\forall j. \quad (23)$$

The terms in the final line of Eq. 23 cancel out because we use our assumption from Section 2.4.1 that the sectors of countries *r* and *s* are identically classified.

Perhaps more importantly, EEBT correlates directly with monetary bilateral trade $\sum_k T_{jk}^{rs} + y_j^{rs}$, and hence Eq. 23 expresses a true trade balance.

Note that total UNFCCC territorial emissions $\sum_i F_i^{(\mathrm{f})s}$ as in Eq. 14 are identical to the total EEBT production-based NEI $\sum_j EEBT_j^{(\mathrm{p})s}$ in Eq. 19, because,

$$EEBT^{(\mathrm{p})s} = \sum_{ij} f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{ij,r\neq s} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right)$$

$$= \sum_i f_i^s x_i^{ss} + \sum_{i,r\neq s} f_i^s x_i^{sr} = \sum_{i,r} f_i^s x_i^{sr}$$

$$= \sum_{ij,r} f_i^s L_{ij}^{sr} y_j^{sr} = \sum_i F_i^{(\mathrm{f})s} = F^{(\mathrm{f})s}. \quad (24)$$

2.4.4. Relationship between EEBT, MRIO footprint, and feedback loops

The EEBT and MRIO methods both produce the same global emissions, but they differ in the way the emissions are allocated to international trade. The EEBT method considers total trade flows with domestic emission intensities, while the MRIO method considers trade only to final consumptions with global emission intensities. Thus, the EEBT method will always yield smaller emission intensities (as it does not include imports), compensated by larger demands (as it includes both intermediate and final consumption). It is difficult to see, without further elaboration, what constitutes the difference between them and if the MRIO or EEBT estimates will be smaller or larger. This section elaborates on the difference between EEBT and MRIO estimates.

Consider the ratio of embodied emissions in import as estimated by the MRIO and EEBT$^{(c)}$ methods:[2]

$$\underbrace{\textstyle\sum_{ijr,s\neq t} f_i^r L_{ij}^{rs} y_j^{st}}_{\text{MRIO}^t} \Big/ \underbrace{\textstyle\sum_{ij,r\neq t} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rt} + y_j^{rt}\right)}_{\text{EEBT}^t}$$

$$= \left(\sum_{ij,r\neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\substack{\text{EEBT}\\ \text{multiplier}}} y_j^{rt} + \sum_{ijr\neq s,s\neq t} \underbrace{f_i^r L_{ij}^{rs}}_{\substack{\text{MRIO}\\ \text{multiplier}}} y_j^{st} \right)$$

$$\Big/ \sum_{ij,r\neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\text{EEBT multiplier}} \left(\sum_k T_{jk}^{rt} + y_j^{rt}\right).$$

In order to simplify this expression, we need to re-index the term $f_i^r L_{ij}^{rs}$ and y_j^{rt}, and obtain

$$MRIO^t / EEBT^t$$

$$= \sum_{ijr\neq t}\Big(\underbrace{f_i^r L_{ij}^{rr}}_{\substack{\text{EEBT}\\ \text{multiplier}}} + \underbrace{\textstyle\sum_s f_i^s L_{ij}^{sr}}_{\substack{\text{MRIO}\\ \text{multiplier}}} \Big) \underbrace{y_j^{rt}}_{\substack{\text{trade into}\\ \text{final cons'n}}} \Big/ \sum_{ij,r\neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\substack{\text{EEBT}\\ \text{multiplier}}} \Big(\underbrace{\textstyle\sum_k T_{jk}^{rt}}_{\substack{\text{trade into}\\ \text{intermed}}} + \underbrace{y_j^{rt}}_{\substack{\text{trade into}\\ \text{final cons'n}}} \Big)$$

$$= \alpha/\beta \tag{25}$$

where a = trade final cons'n / total trade and β = EEBT multiplier / MRIO multiplier.

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[2] Cons'n = consumption; intermed = intermediate.

This expression helps explain the difference between imports for the MRIO and EEBT methods. If there is no import to final consumers then $a = 0$ and the MRIO methods gives zero emissions, while the EEBT method gives a non-zero emission figure as it includes trade into intermediate consumption. If there is no import into intermediate consumption then $a = 1$ and since $\beta \leq 1$ then the MRIO method will yield larger emissions trade, with the difference dependent on the relative size of the emission intensities. If the MRIO emission intensity includes a negligible import component, then $\beta \approx 1$ and the EEBT method will yield larger emissions trade, with the difference dependent on the relative share of imports into intermediate consumption in total imports. If the MRIO emission intensity is dominated by the import component, then $\beta \approx 0$, and the MRIO method will yield larger emissions trade, with the difference dependent on the relative share of imports to intermediate consumption in total imports (see Fig. 2.4).

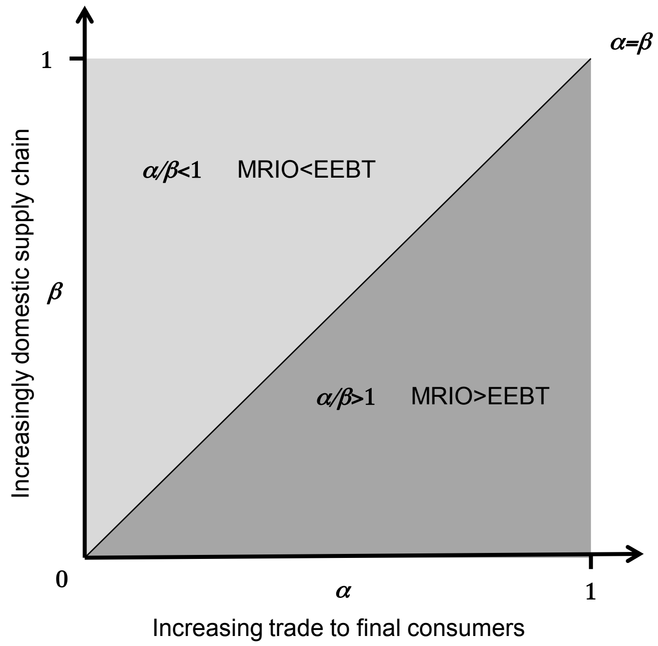

Fig. 2.4: Schematic illustrating the differences between emissions embodied in trade determined by the MRIO and EEBT methods.

2.5. Discussion and conclusions

Our analysis has shown different ways of comparing the emissions associated with production, consumption, and international trade. With the growing interest in consumption-based accounting of factor use, the means of comparing with production-based accounts is becoming more important; the difference between the two is related to the emissions embodied in international trade.

We considered several ways of comparing emission inventories, and how a “trade balance” could be defined. Perhaps the most obvious way to compare production and consumption is through their difference (Section 2.4.1). However, as we show, this does not have desirable properties of a trade balance, as the production and consumption inventories have a different system boundary, and hence the difference should not be interpreted as a trade balance. We show that it is possible to arrive at a consistently defined trade balance in MRIO terms (Section 2.4.2), but this requires an arguably unintuitive definition of production (Eq. 18). In addition, the “trade” in an MRIO trade balance only includes international trade in final goods, because intermediate goods are treated endogenously in any IO model. Outside of the IO community, this treatment of international trade may be seen as unusual and inconsistent with common notions of a monetary trade balance. Finally we discuss the EEBT method which compares linked single-region IO models that consider domestic emissions together with trade in both intermediate and final consumption. While the EEBT formulation has the desirable properties of a trade balance, it is arguably not appropriate to create a consumption-based inventory as the inventory would only include domestic supply chains. Each method of comparison has advantages and disadvantages, and also addresses different questions, thus preference of one method over another, in all circumstances, is potentially ill-advised.

Given their differences, it is worth considering which trade balance formulations would be used for different research or policy questions. If consumption-based emissions of different countries were to be compared, we would suggest an MRIO approach because of the global emissions coverage inherent in this method (Section 2.4.2). The difference between a country's territorial and consumption-based inventory (Section 2.4.1), and how it changes over time, would be a useful indicator of a country's progress towards policy objectives (Peters, Minx, et al., 2011). However, as we showed earlier, this difference does not have the standard properties of a monetary trade balance. Thus, care is needed to emphasize that it is a difference of inventories and not a trade balance.

If trade-adjusted emission inventories (leading to a trade balance) are to be compared, we would suggest an EEBT approach due to the consistency with a monetary trade balance (Section 2.4.3). This method is however not appropriate for consumption analysis as it does not include international supply chains. When using the EEBT method, careful framing is needed to emphasize the system boundary. Framing a policy question as, for example, "what are our territorial emissions to produce exported products" requires a territorial system boundary and hence an EEBT approach. While from an export perspective the use of EEBT may seem more intuitive, it is less intuitive when framed in terms of imports. For example, "what are the emissions to produce imported products" could imply the analysis of global supply chains and the use of the MRIO method. In both cases, careful framing of the research question and definitions is required to avoid confusion.

The discussion and relative merits of trade balances and comparisons in an EEBT or MRIO setting arguably requires more discussion in the IO community (Peters, 2008). A common misperception is that the EEBT method is "incomplete" as it only considers domestic supply chains, however, in compensation it considers total trade exogenously. MRIO, on the other hand, considers trade in final products exogenously but trade in intermediate products endogenously. It is not possible to determine, without performing an analysis, if the MRIO or EEBT measure of consumption is higher or lower in a region (see Eq. 25). As shown in earlier work, the two methods lead to the same global emissions, but different allocations to countries and sectors (Peters, Andrew, et al., 2011). It is possible to present both sets of results (MRIO and EEBT) in the same presentation, but with different framing (Atkinson et al., 2011; Peters & Solli, 2010). A comparison of results from MRIO and EEBT calculations can also give insight into the role of processing trade in different economies. EEBT is potentially easier for fast calculations of time-series, but MRIO is more accurate (Peters, Minx, et al., 2011). Through this article we hope that we have demonstrated some of the key issues in drawing comparisons between production, consumption, and international trade, and ideally this leads to a more consistent treatment of differences and trade balances in future studies.

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Technology, 46(1), 172–9. Copyright 2012 American Chemical Society. http://dx.doi.org/10.1021/es202239t

3. Mapping the structure of the world economy

3.1. Discussion and conclusions

In 2009, China's chief climate negotiator Li Gao argued that carbon emissions due to the production of export goods should be the responsibility of the consuming country (BBC News, 2009). Multi-region input-output (MRIO) tables are acknowledged to be an appropriate tool to underpin this consumer-responsibility accounting (Peters, 2010b; Wiedmann et al., 2007; Wiedmann, 2009). MRIO tables document thousands of relationships between industry sectors (so-called "production recipes") and are thus able to trace carbon emissions through complex international trade and supply chains networks. We present a new MRIO database called Eora that substantially advances the state of the art and contains the world's largest and most detailed map of the global economy.

Wiedmann et al., (2011) provide a comprehensive account of the policy relevance of MRIO applications in a world where consumption and production are increasingly spatially separated. MRIO tables are used to establish the carbon footprints of nations (Hertwich & Peters, 2009), a concept that complements the conventional territorial allocation of emissions as reported to the UNFCCC with a consumer-responsibility perspective of global CO_2 emissions (Minx et al., 2009;

Wiedmann et al., 2010). Carbon footprint results obtained from such MRIO tables have demonstrated the marked growth of emissions facilitated by international trade (Davis et al., 2011; Peters, Minx, et al., 2011; Wiedmann et al., 2010). MRIO tables also have applications in advanced techniques for Life-Cycle Assessment (LCA), where product- and process-specific data are combined with overarching input-output data (Suh et al., 2004).

Tab. 3.1: Performance comparison of the Eora MRIO database with the previous state of art.

	Previous state of art (Wiedmann et al., 2011)	Eora
Country coverage	43-57 individual countries plus 129 regions	187 individual countries
Sector coverage	3760-7353 sectors[1,2]	15909 sectors[1,3]
Environmental indicator coverage	30 emission types 80 resource types	35 indicator categories > 1700 single indicators[4]
Continuity	1995-2007[5]	Annual tables 1990-2010
Timeliness	Publication delayed by at least 5 years	1-2 years prior to current year
Reliability and uncertainty information	None	Standard deviations for every MRIO element

Notes: [1]A "sector" can be an industry or a product. The values listed in Tab. 1 include the number of both industries and products, since some countries feature asymmetrical Supply-Use Tables (SUTs) in which these numbers are different. [2] GTAP 8: 57 sectors and 129 regions for 2004 and 2007, in total 7353 transactions; EXIOPOL: EU27 and 16 non-EU countries, and about 129 sectors for 2000, in total 5547 sectors; WIOD: 27 EU countries and 13 other major countries in the world, more than 35 industries and at least 59 products for 12 years, in total 3760 sectors. [3] 187 single countries at 25-500 sectors totalling 15909 sectors, 5 valuation sheets, 20 years, makes in total more than 20 billion transactions. [4] Energy, CO_2, CH_4, N_2O, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-23, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10-mee, C_2F_6, C_3F_8, C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}, CF_4, c-C_4F_8, SF_6, HANPP, CO, NO_x, NMVOC, NH_3, SO_2, HC, HCFC-141b HCFC-142b, Ecological Footprint, and Water Footprint. [5] GTAP: 1992, 1995, 1997, 2001, 2004, 2007; EXIOPOL: 2000; WIOD: 1995-2009.

The widespread adoption of MRIO models has so far been hampered by a number of factors. First, constructing an MRIO database has been labour-intensive. Second, currently available MRIO tables either do not cover the entire world, and/or group a large number of individual countries into regions, and/or aggregate detailed industries into broad sectors. Third, MRIO tables are often not available as a long, continuous time series, and at the time of their release, the most recent tables are already many years outdated. Finally, MRIO databases currently provide only results without accompanying estimates of reliability and uncertainty. Of course, existing MRIO databases are designed with different purposes in mind, however limited resolution and untimeliness are impediments for any MRIO application, no matter its purpose (Wiedmann et al., 2011). All these shortcomings are mainly due to problems in handling of incomplete, conflicting and mis-aligned data, but also due to previous limitations in computational capacity.

The research needs listed above are now addressed by the new Eora MRIO database. Measured in terms of detail, coverage, size, continuity, timeliness, and comprehensiveness, Eora has considerably extended current limits (Tab. 3.1).

3.2. Methods

3.2.1. Input-output analysis

Leontief's input-output analysis (IOA) framework is at the heart of many models informing national economic policy. Input-output tables that map the production recipes and trade structures in national economies are published regularly by more than 100 national statistical agencies around the world, as well as supranational institutions such as the OECD or Eurostat. Leontief envisaged input-output analysis to be applied to environmental issues (Leontief, 1970), and since then his design of an environmentally-extended input-output table has been employed in thousands of empirical and theoretical studies (R Hoekstra, 2010) (*Appendix*, Text S3.1).

In the 1970s and 1980s, Leontief already had a vision of an information system for the world economy (Leontief, 1974, 1986). However, only during the past two decades, possibly driven by the increasingly complex interdependence of national economies through international trade, and contemporary global problems such as climate change and resource depletion, has research veered more towards multi-regional input-output (MRIO) databases (Wiedmann, 2009).

In contrast to national IO tables, global MRIO databases are not compiled by statistical agencies, but by a handful of research groups around the world.

3.2.2. Construction of the MRIO tables and satellite accounts

There exist serial and parallel approaches to estimating a time series of input-output tables (Temurshoev, Webb, & Yamano, 2011). A serial, iterative approach was chosen for constructing the Eora tables because it has advantages over parallel approaches in situations where the data required for setting up annual initial estimates are unaligned or incomplete (Lenzen, Pinto de Moura, Geschke, Kanemoto, & Moran, 2012). We first generate an initial estimate in accordance with United Nations guidelines (United Nations, 1999) from a selected set of raw data for the base year 2000 (*Appendix*, Text S3.3), because data availability is best for this year (*Appendix*, Table S3.3). In the case of countries for which an input-output table is unavailable we construct a proxy input-output table combining other macro-economic data for these countries with a template input-output structure based on an average of the Australia, Japan, and USA tables (*Appendix*, Table S3.1). We then determine a year-2000 MRIO table by reconciling all raw data available for 2000. This year-2000 MRIO table is taken as the initial estimate for the subsequent year 2001. A 2001 MRIO table is then calculated on the basis of all raw data available for 2001, and the entire time series is completed in the same step-wise manner.

The solution of the reconciliation process for each year is hence obtained from two ingredients: an initial estimate, and a set of raw data. The entire MRIO table construction procedure can be summarised in five steps:

1. All raw data (assume M points) available for the year in question are collated into a vector $\mathbf{c}$ (all data sources are listed in *Appendix* Text S3.6). Since the Eora tables distinguish 5 valuations, including basic prices, margins, taxes and subsidies, no transformation of raw data expressed in purchasers' prices into basic prices is necessary.
2. An $M \times N$ matrix $\mathbf{G}$ is set up that contains constraints coefficients describing the relationship $\mathbf{Ga} = \mathbf{c}$ between M raw data points in $\mathbf{c}$, and N MRIO table elements (vectorised as a $N \times 1$ vector $\mathbf{a}$). In addition, $N \times 1$ vectors $\mathbf{l}$ and $\mathbf{u}$ are constructed that contain lower and upper bounds on all MRIO elements in $\mathbf{a}$. These lower and upper bounds result from definitions of accounting variables. For example, the bounds for changes in inventories are $[-\infty,+\infty]$, those for subsidies are $[-\infty,0]$, and those for remaining MRIO elements are $[0,+\infty]$.
3. Constraints based on raw data stemming from different sources often conflict, so that $\mathbf{Ga} = \mathbf{c}$ can usually not be fulfilled exactly. We therefore follow van der Ploeg (1988) by extending the vector $\mathbf{a}$ with slack variables

$\mathbf{e} = \mathbf{Ga} - \mathbf{c}$, effectively allowing the MRIO realisations $\mathbf{Ga}$ to deviate from their prescribed values $\mathbf{c}$. $\mathbf{a}$ and $\mathbf{e}$ are collated into one vector $\mathbf{p} = [\mathbf{a}|\mathbf{e}]'$.

4. A constrained optimisation algorithm is invoked for finding a reconciled solution for $\mathbf{p}$ that best fulfils the constraints $\mathbf{Gp} = \mathbf{c}$ and $\mathbf{l} \leq \mathbf{p} \leq \mathbf{u}$, whilst minimising the departure of $\mathbf{p}$ from its initial estimate $\mathbf{p}_0 = [\mathbf{a}_0|\mathbf{0}]'$. The optimisation step is necessary because the number of MRIO elements by far exceeds the number of constraints and there is not enough information to analytically solve the system for $\mathbf{p}$. The objectives "best fulfils" and "minimises departure" can be specified mathematically. For example, in the approach by van der Ploeg (1988), "best" means minimising the slack variables $\mathbf{e}$.
5. The time series is constructed iteratively, by starting with the 2000 initial estimate, reconciling this with all 2000 constraints, and taking the solution as the initial estimate for 2001, and so on. Back-casting to 1990 proceeds similarly. A balanced table for one year will be an inappropriate initial estimate for the next year under strong economic growth. Therefore, we have constructed initial estimates by scaling all prior solutions with inter-year ratios specific to transactions (use, trade), final demand, value added, and supply tables. These ratios were derived from country time series data on GDP, exports, imports, and value added (United Nations Statistics Division, 2011a).

A simple example is provided in the *Appendix*, Text S3.5.

Whilst there exists a plethora of optimisation approaches, the literature on input-output table estimation favours variants of the RAS iterative scaling method (Bacharach, 1970), and Quadratic Programming algorithms (van der Ploeg, 1988). These methods differ by the quantitative specification for penalties that are imposed for any departure from the constraints $\mathbf{Gp} = \mathbf{c}$ and $\mathbf{l} \leq \mathbf{p} \leq \mathbf{u}$ (Fig. 3.1). Balancing and time series iteration are discussed further in the *Appendix*, Text S3.2.

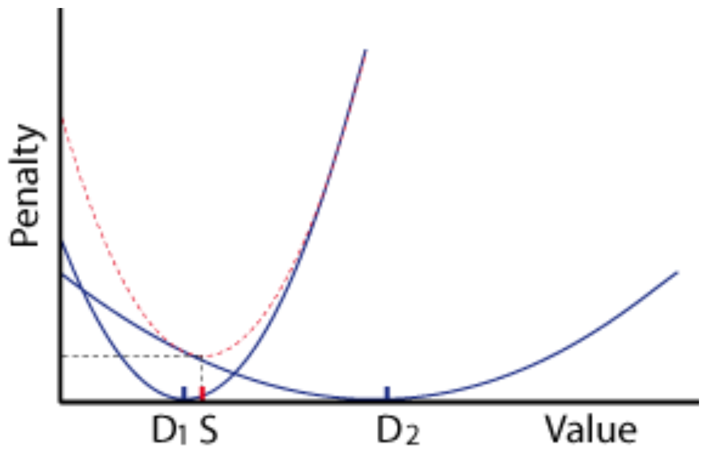


Fig. 3.1: Schematic representation of a compromise solution between two conflicting data points. Points D_1 and D_2 represent two conflicting reported values of the same data point. D_1 has high confidence (a small standard deviation) and D_2 has low confidence (large standard deviation). The solution point S lies closer to D_1. This schematic shows a quadratic penalty function. Using linear, entropy, or another objective function will result in the solution S representing a different compromise between the two constraints.

A key feature of the optimisers used for constructing Eora MRIO tables is their ability to deal with conflicting constraints. A prime example for such data conflict are exports and imports data contained in the United Nations' Comtrade database (United Nations, 2011). One would expect that bilateral trade volumes, reported by the exporting country exclusive of international trade margins and import duties, are slightly smaller but comparable in magnitude to the corresponding volumes reported by the importing country (Oosterhaven et al., 2008). However, a surprisingly large proportion of the data violate this basic requirement (Fig. 3.2).

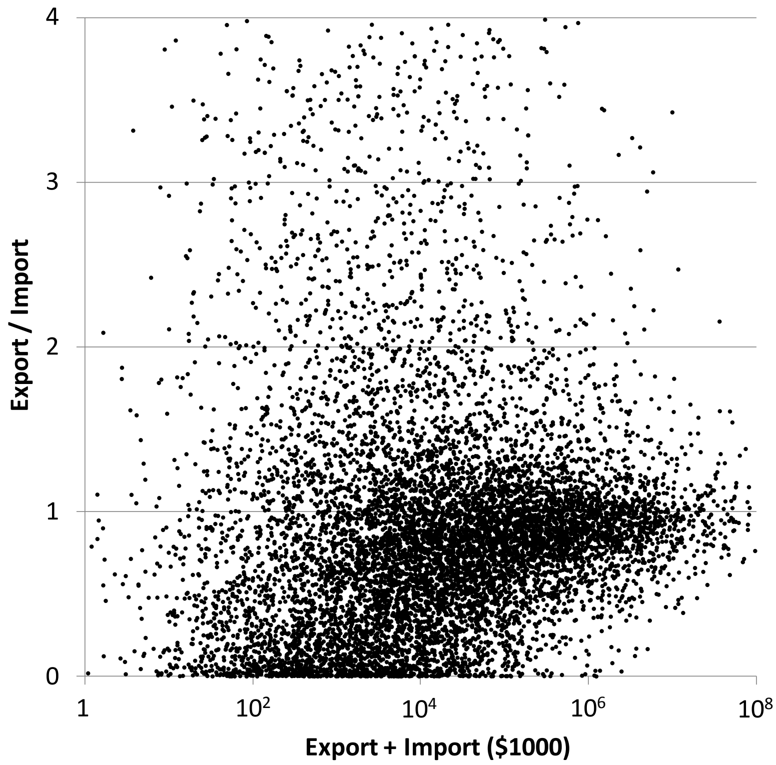


Fig. 3.2: Data conflict in the United Nations Comtrade database (United Nations,

2011). The scatter plot contains 187^2 bilateral national trade volumes. The horizontal line crossing the vertical axis at 1 means country A's reported exports to country B equal country B's reported imports from A. Reported imports should be slightly larger, so that in theory there should be no values above the said horizontal line. This principle is clearly violated, though integrity does improve slightly with larger trade values. Resolving fundamental disagreement in the original data such as this is a major challenge Eora attempts to solve.

This circumstance imposes restrictions on the choice of optimiser, in the sense that conflicting equations in the linear system $\mathbf{Gp} = \mathbf{c}$ render the balancing and reconciling of the Eora MRIO tables an infeasible problem for the most widely used RAS method. The problem of conflicting raw data can only be solved through the introduction of quantitative information on data reliability and uncertainty, slack variables $\mathbf{e}$, and through combining this information with advanced optimisation methods such as Quadratic Programming and KRAS (Lenzen, Gallego, & Wood, 2009). Variants of these methods have been implemented in the Eora optimiser suite.

Note that the constraints coefficients matrix $\mathbf{G}$ is sparse, but very large. Since for an average time series year, we were able to locate about 70 million raw data points, and our MRIO has more than one billion elements for each year, $\mathbf{G}$ has about 70 million rows, and more than 1 billion columns. The timely construction of $\mathbf{G}$ was achieved by automating data mining, processing and re-classification procedures as much as possible (Geschke, Lenzen, Kanemoto, & Moran, 2011; Yu, Lenzen, Dey, & Badcock, 2009) (see *Appendix*, Text S3.4). The design and implementation of constrained optimisers on such a large scale is an achievement in itself, since variable spaces sized in excess of 1 billion are beyond the capability of commercially available software (see Section 3.1). We constructed, balanced, and reconciled Eora's large MRIOs on a purpose-built scientific computing cluster. Tables currently deployed online have been generated using a parallelised version of KRAS (Lenzen et al., 2009). We provide further details on the implementation of steps 1-5 in Section 3.1.

3.2.3. Construction of the standard deviations table

The standard deviations σ_{p_j} accompanying MRIO elements $\mathbf{p}_j$ are estimated in two steps. First, assuming normally distributed observations, standard deviations σ_{c_i} of raw data points c_i are partly estimated based on published data or expert interviews, but mostly set according to a certain world views on the uncertainty of various sets of raw data. For example, our interviews revealed that input-output data issued by national statistical offices are widely viewed as accurate representations of "true" input-output transactions, whereas for example United Nations statistical officers acknowledged limitations in their ability to interrogate and correct data supplied to them from various sources. Hence, the version of Eora available at the time of writing was constructed with national data being set "tight" (i.e. small standard deviations), and UN data "loose" (large standard deviations). Different specifications based on different world views are possible, and if re-run, would result in a different version of Eora. There is hence no unique, “true” set of MRIO tables (Lenzen, Moran, Kanemoto, & Geschke, 2012). Nevertheless, it can generally be found that smaller raw data values are associated with higher relative standard deviations, and vice versa.

Second, a modified RAS optimisation algorithm is employed in order to fit standard deviations σ_{p_j} to an error propagation formula $\sigma_{c_i} = \sqrt{\sum_j \left(G_{ij}\sigma_{p_j}\right)^2}$. This procedure is consistent with the estimation of the MRIO elements **p**, based on raw data **c**. In fact, the error propagation formula can be derived from the optimisation condition $\mathbf{Gp} = \mathbf{c}$. The $\boldsymbol{s}_p$ are influenced by two factors. The first is an uncertainty characteristic: the smaller the uncertainty $\boldsymbol{s}_c$ of a raw data item c, the smaller the uncertainty $\boldsymbol{s}_p$ of MRIO elements addressed by this raw data item. The second is a data conflict characteristic: the pre-modified-RAS initial estimate $\boldsymbol{\sigma}_{\boldsymbol{p}_0}$ of the $\boldsymbol{s}_p$ is set to the difference between the MRIO initial estimate $\mathbf{p}_0$ and the MRIO final solution **p**. This difference is influenced by the conflict in the raw data, because conflicting raw data lead to movements in elements during optimizer runs. For further details see (Lenzen, Wood, & Wiedmann, 2010).

3.3. The Eora global MRIO information system

3.3.1. Structure and innovations

The Eora MRIO database is deployed online (www.worldmrio.com). Its main feature is a continuous series of environmentally extended global MRIO tables. Each MRIO table is a representation of the structure of the global economy; it contains a complete account of monetary transactions between the industry sectors of 187 countries (*Appendix*, Table S3.2). Because each country has a different economic structure, most of Eora's countries are represented by different table formats (*Appendix*, Text S3.1), and at a different level of sector detail, ranging from 26 to 500 sectors per country (*Appendix*, Table S3.2).

The strategy of heterogeneous sector classification and table type was chosen so that the Eora MRIO could incorporate maximum sector detail overall. For example, the economies of Brazil, China and Singapore are heavily based on agriculture, manufacturing, and trade/services, respectively. To represent these economies in a homogeneous sector classification as in existing MRIOs requires substantial aggregation and reclassification steps (Oosterhaven et al., 2008), and causes loss of information and transparency. In addition, Eora's heterogeneous sector classification ensures flexibility, because a homogeneous MRIO time series where all countries' transactions are expressed in the same sector classification can always be calculated from the original heterogeneous MRIO tables. Complementing the full table, a 26-sector homogeneously-classified version is available for download from the Eora website.

Each monetary MRIO table identifies 15909 sectors, both supplying and receiving, and hence in excess of 250 million transactions. Basic prices of transactions are valued separately to trade margins, transport margins, taxes and subsidies, in five valuation sheets, expressed in units of current US$ (see Fig. 3.3 for a heat map of the 2009 basic price table). The tables exist in a constant format and sector/indicator classification for a 20-year period 1990-2010. The total number of transactions data exceeds 1 billion per year, or 20 billion in total, and including the constraint matrices, satellite accounts, and ancillary result files and reports, that complete result time series occupies more than 3 Terabytes.

Environmentally extended MRIOs append so-called satellite accounts in physical units, which complement the monetary table with non-monetary inputs to production. Thus the production recipes contained in an environmentally extended MRIO include the conventional economic inputs (steel, machinery, labour, capital) as well as resources (land, energy, water) and environmental impacts (emissions, biodiversity loss). The strength of this set-up is that both the monetary MRIO and the satellite accounts adhere to the same sector classification. This data integration enables the straightforward translation of economic activity in one country into biophysical impacts in another. Hence, environmentally extended MRIOs provide a powerful tool and data set to a wide range of footprinting and LCA applications.

Eora's satellite accounts provide details on 35 broad indicator groups. At the finest level of detail (fuel types, gas types, individual threatened species), these indicator groups break down into 20,832 indicator line items.

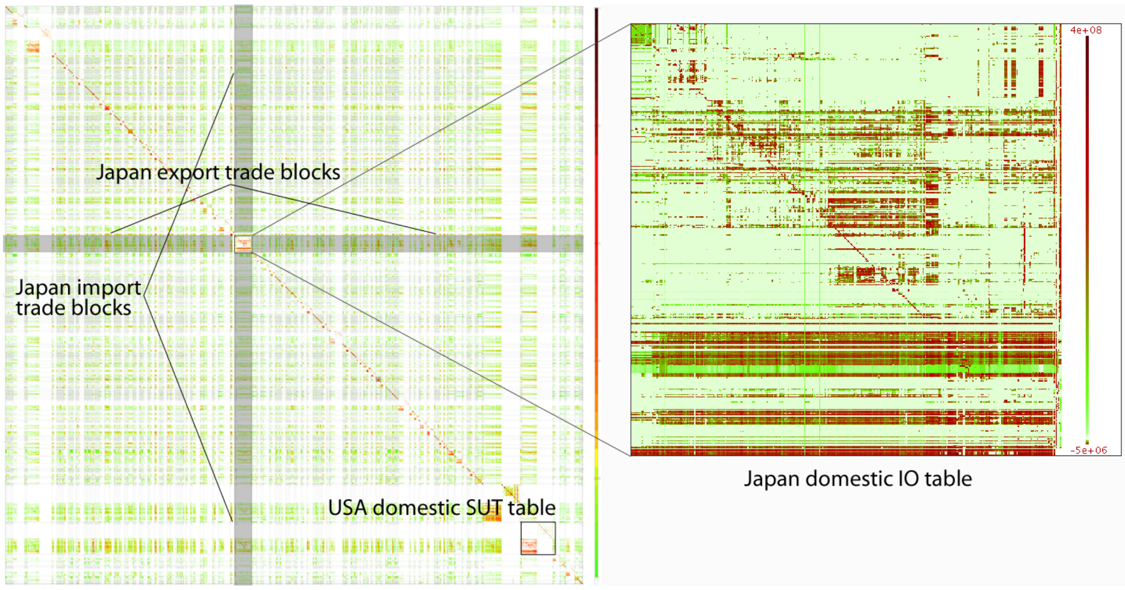


Fig. 3.3: Heat map of the Eora MRIO 2009 basic price table, with call-out of the Japan domestic IO table. Each pixel encodes the total value of transactions from one sector to another. As seen in the colourmap legend at right, darker red pixels represent larger values. The Eora MRIO time series (1990-2010) represents 187 countries with total of more than 15,000 sectors and has five valuation layers.

In order to assemble and balance MRIO tables at such a large scale, a host of obstacles had to be overcome by developing a number of innovative features: 1) a streamlined, automated workflow management including a custom-built programming language, 2) a novel constrained optimisation algorithm that can solve large-scale quadratic programming problems, and 3) a tailored hardware configuration for parallelised handling of the Eora build-pipeline (see *Appendix*, Text S3.2.4).

3.3.2. Uncertainty information

A unique and innovative feature of the Eora MRIO tables is that every MRIO and satellite account element is accompanied by corresponding standard deviations. Transparent information on uncertainty is important in any application of input-output analysis, because it helps decision-makers in understanding assumptions and limitations underlying the data, and thus enables them to engage in informed and transparent decision-making.

One example for applications of IO tables are increasingly widespread hybrid approaches to life-cycle assessment (LCA) that combine detailed bottom-up process information with comprehensive top-down input-output information (Suh et al., 2004). LCA is often used in comparative assessments, for example of technology options. In order to decide whether one option is preferable over others, it is not sufficient to simply consider final LCA results. Depending on the standard deviations associated with these results, decisions may well be different after uncertainty information is taken into account.

Similarly, comparative carbon footprint studies that utilise carbon multipliers derived from global MRIO models should always be accompanied by transparent and comprehensible uncertainty estimates. Only then can decisions be supported by measures of statistical significance, for example using hypothesis testing.

In Eora, MRIO standard deviations are calculated by fitting an error propagation formula to standard deviations of the raw data points. This method is described in detail elsewhere (Lenzen, Wood, et al., 2010). Standard deviations of multipliers can be derived from MRIO standard deviations using Monte-Carlo techniques (Bullard & Sebald, 1988). Standard deviations are essential for determining the uncertainty of any quantitative measure derived from MRIO tables. Moreover, error propagation theory yields that relative standard deviations decrease with aggregation, so that Eora's quantitative estimates of standard deviations of MRIO elements enable analysts to aggregate the Eora tables according to their own uncertainty requirements.

The Eora website offers tabular and graphic information on the reliability of MRIO blocks, separately for every country and year. Tabular information includes two ranked lists of raw data points that are best/least represented by the MRIO table. An example for a visualisation of MRIO table reliability is what we call a *rocket plot* (Fig. 3.4).

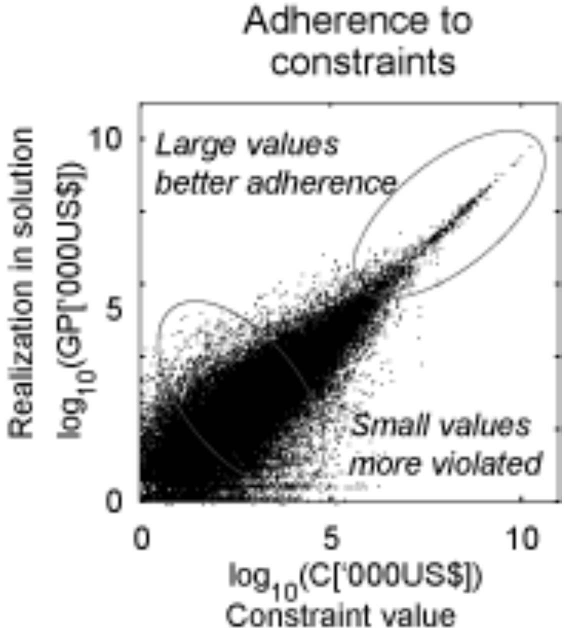


Fig. 3.4: Rocket plot of constraints and their adherence in the MRIO solution, shown here for the United States. Large constraint values (increasing along the logarithmic horizontal axis) are more reliable and thus the MRIO elements addressed by these constraints are better preserved in the final MRIO (logarithmic vertical axis). Small constraint values are less reliable and thus less adhered to in the final realized MRIO.

In agreement with previous studies, and in turn with our uncertainty specifications of raw data items, we find that large transactions are better represented than small ones. This is because the optimisation of any large multi-region input-output (MRIO) table is an underdetermined optimisation problem: The number of raw data items that can serve as support points for the MRIO table is much smaller than the number of MRIO table elements. Those elements that are supported by only a few raw data points, and hence restricted by only a few constraints, can be subject to large adjustments during an optimisation run, and hence their reliability is low. On the other hands, for virtually all large and important MRIO table elements, there exist supporting raw data, so that the adjustment of these elements is minimal, and hence their reliability is high (Fig. 3.4).

Even though many MRIO elements are supported by only few raw data points, one can show using Monte-Carlo techniques that it is always beneficial for MRIO table construction to exploit as much information as possible (Lenzen, 2011). This principle also refers to the inclusion in the Eora MRIO table of countries for which input-output tables must be estimated as no official tables are available. For all Eora countries there exists at least some sectoral breakdown of final demand (United Nations Statistics Division, 2011b) and value added (United Nations Statistics Division, 2011c), plus detailed data on international commodity trade (United Nations, 2011), which can be used to infer their input-output structure. Such estimates, however coarse, provide more information than the regional country aggregates in existing global MRIO databases.

Despite their abundance, small and unreliable MRIO elements are unlikely to significantly distort input-output multipliers (Jensen & West, 1980; Jensen, 1980), and therefore do not compromise the quality of footprints, LCA results, and other policy-relevant measures.

3.3.3. Validation

We validated our results by comparison with footprint studies by Peters *et al* (2011b), GFN (Global Footprint Network, 2010) and the Water Footprint Network (Mekonnen & Hoekstra, 2011). As seen in Fig. 3.5 the Eora-based results are in line with the national carbon footprint (CF), water footprint (WF), and Ecological Footprint (EF) results calculated in these other studies.

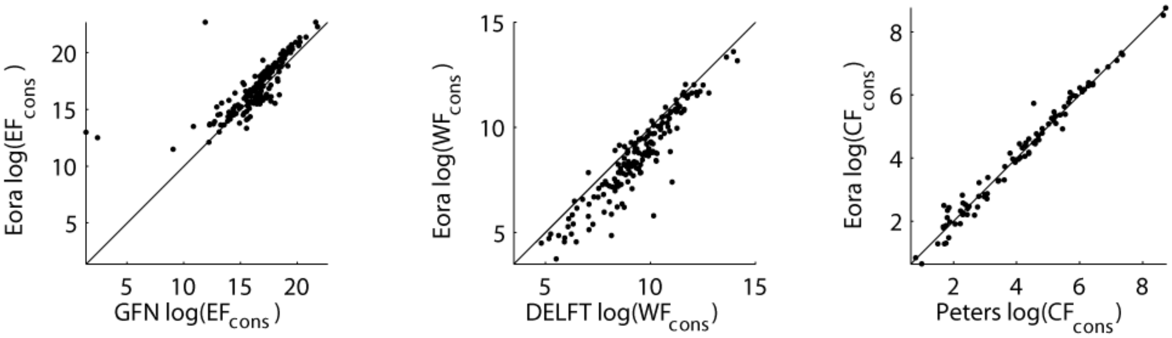


Fig. 3.5: Comparison of final national Ecological Footprint (EF) of consumption in 2007, water footprint (WF) in 2000, and CO_2 footprint (CF) in 2008 as calculated by Eora and other authors. The Eora-based results are in line with the results reached by other studies.

3.4. Potential applications

In addition to MRIO table elements and their standard deviation the Eora database supports a range of analytical concepts. The most overarching of these are national accounts balances. Such balances are known from economic statistics where they reflect, in monetary units, that for each nation, production plus imports must equal consumption plus exports. Being an environmentally-extended MRIO framework, Eora also shows national account balances in terms of the environmental indicators quantified in the satellite accounts, in physical units of tonnes of emissions, litres of water, etc. The production column of each balance table contains the territorial use of resources or emission of pollutants. The exports and imports columns can be interpreted as resources and pollutants embodied in international trade. The consumption column reflects the country's footprint in terms of the respective indicator. Footprints are calculated from environmental multipliers in the standard manner using the Leontief inverse.

In policy contexts the production account is also interpreted as the producer-responsibility perspective whilst the footprint account represents the consumer-responsibility perspective (Munksgaard & Pedersen, 2001; Peters & Hertwich, 2008a). Whilst most national and global data compendia portray environmental variables as characteristics by territory, recent thinking emphasises the view that resource use and emissions are ultimately driven by consumers who, through their demand, require production, and as a consequence, drive environmental pressure. For example, Eora data confirm earlier findings of a carbon footprint study of the UK (Wiedmann et al., 2010) showing that the UK was outsourcing its emissions-intensive production by importing from overseas, and that – counter to UK government claims – the UK's actual carbon footprint had been increasing. This finding prompted the British Minister for the Environment to address the public on BBC Radio (2008), and led to a public inquiry by the UK Government Select Committee on Climate Change (Barrett, Roelich, Peters, Wiedmann, & Lenzen, 2012; Energy and Climate Change Committee, 2011). A flow map visualization showing embodied CO_2 imports into the UK is shown in Fig. 3.6.

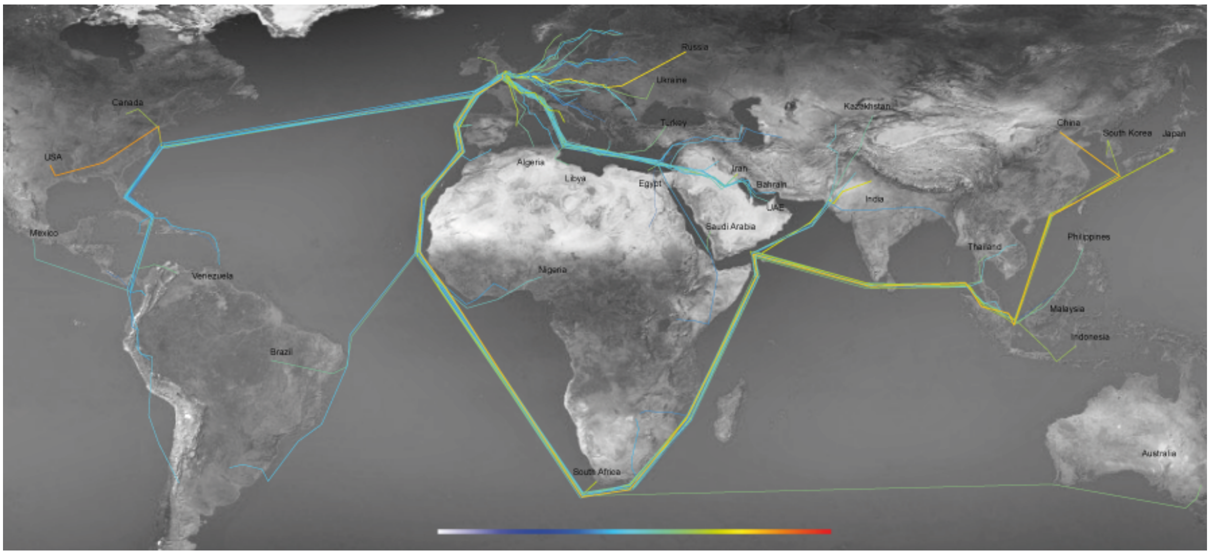


Fig. 3.6: Global flow map of embodied energy consumed in the UK. Energy used in the USA to produce goods finally used by UK consumers is illustrated by a line between USA and UK. Red, yellow, and green lines encode larger values. Line width encodes flow magnitude.

The Eora database contains annual national accounts balances for the entire period 1990-2010, for every country, in monetary terms as well as for every satellite indicator. Such balances reveal which countries are net exporters or net importers of environmental pressure.

Whilst there exist several carbon, water and ecological footprint studies based on global MRIOs, these have not yet been widely utilised in LCA studies. Nevertheless, the potential for future MRIO-assisted LCA applications is large, especially when MRIO databases feature sufficiently high country and sector detail to be able to integrate with detailed bottom-up, process-specific data. The global coverage of MRIOs is particularly important given that manufacturing processes increasingly draw on raw and semi-fabricated intermediate inputs sourced from global locations with comparative cost advantages. It is not uncommon for consumer products to be underpinned by global supply-chain networks involving dozens of countries (Wiedmann et al., 2011).

Individual supply chains can be isolated from the MRIO using a technique called *Structural Path Analysis* (SPA) (Defourny & Thorbecke, 1984). SPA uses tree-scanning algorithms to trace and extract the most important paths from the network, and to rank paths according to their financial magnitude or according to their content of CO_2, embodied air pollution, or any other satellite indicator. The Eora database provides ranked SPAs for all satellite indicators. SPA can be used to investigate supply chains originating, or ending, in a certain country and/or sector (Fig. 3.5), or to identify supply chains passing through a sector of interest. SPAs provide a versatile microscopic sectoral and geographic view of the aggregates in the macroscopic national account, footprint, and LCA measures.

A widely used technique for identifying drivers of change is *Structural Decomposition Analysis* (SDA) (Rutger Hoekstra & van der Bergh, 2002). SDA has been used for unravelling the roles of technological change, production structures, demand structures, affluence (per-capita consumption), and population growth, in driving up CO_2 emissions. Understanding of such key drivers is essential for designing policies for mitigating climate change, because such policies are potentially most effective when aimed at the most important structural determinants of emissions. This time series must feature tables in a constant sector classification, and should ideally include a long, continuous sequence of annual tables. The lack of MRIO tables meeting this requirement has so far prevented a comprehensive assessment of global environmental trends.

A key requirement for SDA is the availability of a time series of IO tables expressed in constant prices. The literature on the topic of converting national currency to constant-price US$ appears to recommend the approaches of "convert-first then deflate" and double deflation, i.e. the residual adjustment of value added to achieve the table balance. The literature also recommends the usage of Purchasing Power Parity (PPP) exchange rates (Dell'Ariccia, 1999; Pardey, Roseboom, & Craig, 2012). The conversion and deflation of the transaction tables of Eora's 187 countries can be achieved by using PPP exchange rates published by the OECD (Organization for Economic Co-operation and Development, 2012) and deflators published by U.S. Bureau of Labor Statistics (U.S. Burea of Labor Statistics, 2012). For those countries where PPP exchange rates are not available, market exchange rates published by International Monetary Fund (IMF) can be used (comparing with WIOD practice (Timmer, 2012)). The construction of constant-price Eora tables is part of ongoing work.

In conclusion, the Eora tables represent a major advance in the resolution, timeliness of multi-region input-output (MRIO) tables, and therefore also in the relevance of a wide range of applications such as carbon, water and ecological footprinting, and Life-Cycle Assessment. This advance was possible through the development of a number of innovations such as a data processing language, new optimisation algorithms, advanced computational solutions, and the simultaneous construction of uncertainty estimates.

The free availability of Eora was intended to enable MRIO databases to be accessible to a wider audience of analysts, translating into more frequent usage of MRIO techniques in applications to real-world problems.

The timeliness of Eora means that a host of MRIO time series applications such as Structural Decomposition Analysis will be able to generate more current and relevant results than has been achievable so far. The multi-year delay of publication of input-output tables is one of the most frequently cited reasons for impediments to the uptake of input-output techniques. Timely annual MRIO updates are now significantly more feasible given the high degree of automation in Eora's construction procedures.

The high sector resolution in Eora is especially important if carbon and water footprinting, consumer product labelling, global-corporate emissions reporting, environmental life-cycle assessment (LCA), and similar frameworks underpinning decisions with a demand-side perspective are to attain widespread and high-level policy relevance (Tukker et al., 2009). This is because input-output analysis is increasingly being recognised as an indispensable component of hybrid footprinting and LCA techniques combining the specificity of detailed product and process data with the completeness of comprehensive input-output data (Suh et al., 2004). One of the main perceived weaknesses of existing IO components in footprinting and LCA methods is the apparent lack of sector detail (Wiedmann et al., 2011), and hence the development of the Eora tables was guided by the goal of including then largest possible number of sectors. For example, the production of aluminium and copper entails significantly different levels of electricity use, and therefore emissions. However, if those metal industries were aggregated into a single "nonferrous metals" sector then any copper products, such as motors, would be assigned too high a carbon footprint because it would appear that aluminium was part of the input into motors. Similarly, if aquaculture and open ocean fishing are not distinguished it is impossible to tell whether fish exports from a country come from farms, with fewer sustainability implications, or from open ocean fishing, with potentially serious overfishing and bycatch concerns.

Eora's country resolution is particularly important in applications dealing with biodiversity and poverty indicators, since these are particularly important for developing countries that are not distinguished in existing MRIO databases. Examples of such countries are Madagascar, a global hot spot of endemic species threatened by habitat loss to agriculture (Lenzen, Moran, Kanemoto, Foran, et al., 2012), and Uzbekistan, where foreign demand of cotton places the Aral Lake water metabolism under severe pressure (Bekchanov, Bhaduri, Lenzen, & Lamers, 2012). Any MRIO analysis aimed at identifying the global driving forces of threats to species in Madagascar, and of water use in Uzbekistan, must distinguish these as separate countries.

Finally, it is essential that MRIO information is presented as values along with their standard deviations. Only then can users understand the assumptions and limitations underlying MRIO tables, engage in rational and informed debate, and facilitate transparent decision-making.

4. International trade undermines national emission reduction targets: New evidence from air pollution

4.1. Introduction

The shifting of CO_2 emissions from developed to developing countries is a substantial and growing problem. CO_2 leakage was not formally addressed in the initial Kyoto Protocol discussions as it was anticipated to be a minor issue or one to be addressed later (Intergovernmental Panel on Climate Change, 1995). However estimates now indicate that it is not minor, and that up to 30% of global emissions are linked to production for export (Aichele & Felbermayr, 2011; R. M. Andrew, Davis, & Peters, 2013; Caldeira & Davis, 2011; Chen & Chen, 2011; Hertwich & Peters, 2009; Nakano et al., 2009; Peters, Minx, et al., 2011; Peters, Marland, et al., 2011). A consumption-based inventory of the UK found that growing consumption in the country was supplied by emissions-intensive imports, not new domestic production. Consequently the UK's total carbon footprint increased 12% between 1992 and 2004, not decreased by 5% as its territorial emissions inventory showed (BBC Radio, 2008; Wiedmann et al., 2008, 2010). A recent UK study recommended that consumption-based inventories be constructed as a complement to current territorial emissions inventories (Barrett et al., 2013). In China, estimates show that in 2005 nearly 30% of emissions were linked to production for export (Feng et al., 2013; Weber, Peters, Guan, & Hubacek, 2008). Since export production has played a major role in its emissions growth (Minx et al., 2011), China has argued that responsibility for emissions should lie not just with the producer but also with the final consumers of goods (BBC News, 2009; Information Office of the State Council of China, 2011; Leggett, Logan, & Mackey, 2008). For nearly all large economies the discrepancy between their territorial emissions and their actual carbon footprint is growing.

This study uses a new set of high resolution global multi-region input-output (MRIO) tables (Lenzen, Kanemoto, et al., 2012; Lenzen, Moran, Kanemoto, & Geschke, 2013) to investigate flows of embodied CO_2 and air pollution over time. The Eora tables provide high sector detail, cover 187 countries, and offer a true, not interpolated or proxy-estimated, timeseries from 1970-2011.

Here we present several findings. First, we are able to independently confirm previous findings that adjusting for trade, developed countries emissions have increased, not decreased. Independent confirmation of this result is important given the prominence of consumption-based accounting in setting national and international GHG reduction targets. Our inventories also consider non-CO_2 GHGs, and we confirm the burden-shifting effect is similar, or stronger, for these gasses. Second, we find that the sectors successfully holding or lowering their domestic emissions are the often the same as those increasing their imports of embodied CO_2. This suggests that it is not cleaner production or consumption patterns that are reducing domestic emissions, but simply burden-shifting of the same emissions-intensive activities. Third, we find that 72% of the 200 fastest-growing flows of embodied CO_2 originate outside the Kyoto Annex B signatory nations. These fastest growing flows transport embodied emissions from developing countries both to developed and other developing countries. Finally, we find that historically the same phenomenon of emissions displacement has already occurred for air pollution. The result has been that despite aggressive legislation of SO_x, NO_x and PM_{10} in major emitters, total global air pollution emissions have increased.

4.2. Materials and Methods

All results are based on the Eora environmentally extended multi-region input-output (MRIO) table (Lenzen, Kanemoto, et al., 2012; Lenzen et al., 2013) and are available online at http://worldmrio.com. Input-output tables have long been used to re-attribute pollution from production to final consumers (Kanemoto, Lenzen, Peters, Moran, & Geschke, 2012; Lenzen et al., 2004; Leontief, 1970; Peters, 2008), including for calculating carbon footprints. Eora is one of a new generation of such systems robust enough for policy use (a survey of current systems is provided by Tukker & Dietzenbacher, 2013). Eora advances the state of the art by covering all UNFCCC countries - not just regions or a subset of countries - and provides a consistent, accurately modeled time series from 1970-2011, significantly improved detail, non-CO_2 emissions, and confidence estimates for all results. While it has been shown that increasing the resolution of embodied CO_2 models does not alter the basic results (Davis & Caldeira, 2010; Peters, Davis, & Andrew, 2012), accurate models with complete country coverage are required for policy applications.

The MRIO table can be used to estimate consumption-based inventories of CO_2 and other greenhouse gas emissions. Eora covers 15,909 sectors across 187 countries with IO tables modelled for each year and thus offers substantially more breadth, detail, and accuracy than has yet been achieved. The Eora MRIO also incorporates data on trade in services. However these data are often less detailed and thus the MRIO model has higher uncertainty about embodied emissions transfers due to trade in services. Another limitation of the model used in this study is poorer data availability in 1970-1989. The MRIO in those years is built using the 1990 MRIO table as an initial template then using the constrained optimization method described in (Lenzen, Kanemoto, et al., 2012) with UNSNA MA and OC data as constraints.

The Leontief demand-pull model used to construct consumption-based inventories is a workhorse model that has been well described since its introduction (Leontief, 1970, 1986). For a detailed explanation of how this model is implemented with the Eora MRIO the reader is referred to previously published descriptions (Lenzen, Kanemoto, et al., 2012; Lenzen et al., 2013). Briefly, the method proceeds as follows. Territorial environmental emissions F can be decomposed into consumption-based environmental emissions and embodied environmental emissions in export and import for country s using an MRIO table following Kanemoto et al. (2012) and chapter 2:

$$\underbrace{F_j^s}_{\text{production}} = \sum_r f_i^r \left[\underbrace{\sum_{it} L_{ij}^{rt} y_j^{ts}}_{\text{consumption}} \overbrace{- \underbrace{\sum_{it \neq s} L_{ij}^{rt} y_j^{ts}}_{\text{imports}} + \underbrace{\sum_{it \neq s} L_{ij}^{rs} y_j^{st}}_{\text{exports}}}^{\text{net trade balance}} \right]$$

$$= \sum_r f_i^r \left[\sum_i L_{ij}^{rs} y_j^{ss} + \sum_{it \neq s} L_{ij}^{rs} y_j^{st} \right] = \sum_r f_i^r \sum_{it} L_{ij}^{rs} y_j^{st}$$

where f is emissions intensity, r is the emitter country, L is the Leontief inverse, y is final demand, and i and j are the sectors of origin and destination. "Consumption" covers consumption-based emissions and "imports" means the embodied emissions in imports, where t is the supplying (most recent seller) region and s is the destination country (region). "Exports" covers embodied emissions in exports where s is the last selling and t is the destination region.

Rather than relying on just one emissions data source Eora provides an timeseries of GHG gas and air pollutant emissions built on multiple data sources including: GHG data from the Emission Database for Global Atmospheric

Research (EDGAR), the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory, Eurostat, energy data, linked to CO_2 emissions, from the IEA/OECD, the Energy Information Administration (EIA), the United Nations Statistics Division (UNSD), and Eurostat. All results presented here for CO_2 are exclusive of emissions from land use, land-use change and forestry (LULUCF). It should be noted that Guan, Liu, Geng, Lindner, & Hubacek (2012) found that official Chinese CO_2 emissions estimates may be unreliable; however to our knowledge no better alternative currently exists. Data on ozone depleting substances (ODS) emissions were sourced from the United Nations Environment Program. The full set of data sources is documented in SI S1.

4.3. Results and Discussion

4.3.1. Embodied Emissions Undermine Kyoto Targets

Using the Eora MRIO we confirm earlier findings that much of the apparent success in decreasing domestic emissions has been more than offset by an increase in embodied emissions in imports. For the USA, Japan, most EU nations, and the EU-27 as a whole, the amount of CO_2 burden shifting to developing countries exceeds the size of their Kyoto-specified emissions reduction.

While territorial emissions in these countries have decreased, their total carbon footprint has increased.

According to the territorial emissions inventory developed (Kyoto Annex B listed) countries reduced emissions by 1.59 Gt and developing countries increased emissions by 13.7 Gt during the period 1990-2011. However, after assigning emissions responsibility to consumers we find that developing countries transfer 2.95 Gt of CO_2 to developed countries thorough international trade in 2011. Under a consumer responsibility principle developed countries have not recorded a decrease from 1990 levels but rather an increase.

The Kyoto Protocol Annex B signatories agreed to reduce emissions a total of 0.76 Gt (5.2%) from 1990 levels. The EU as a group has nearly succeeded in meeting its target (due both to intentional action and to economic recession) and Russia and the former Soviet states have reduced emissions even beyond their Kyoto targets. However despite these successful reductions, in 2011 1.67 Gt of CO_2 was embodied in net imports to developed countries. In many countries the magnitude of emissions transfers is on par with that of the original reduction target (Figure 4.1). The United Kingdom and Poland are perhaps the most striking cases for how outsourcing emissions-intensive production has helped countries meet their targets. Both countries report reductions that exceed their Kyoto targets, however once emissions embodied in their imports are included, they no longer achieve these targets. Similar outsourcing can be observed also for countries that either have failed to meet their targets, such as the USA and Japan, or that have met their Kyoto targets even including emissions embodied in imports, such as Russia. Remarkably, in all cases, changes in emissions embodied in imports are comparable to, or larger than, changes in domestic emissions.

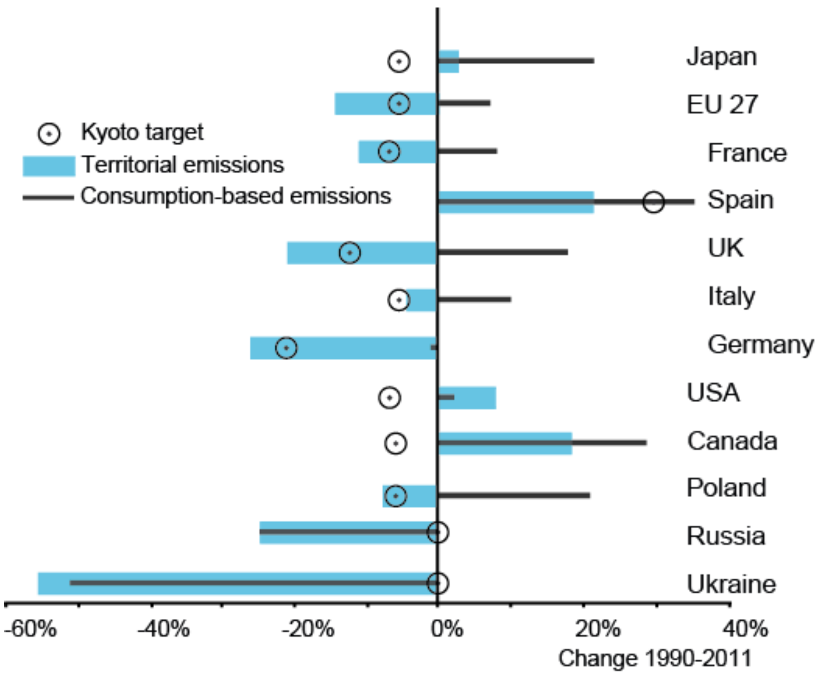


Figure 4.1: Kyoto Protocol emissions targets (circles), territorial emissions (grey bars) with which progress is measured, and consumption-based emissions (black bars). Many major emitters appear to be progressing toward their Kyoto targets yet their actual carbon footprints are increasing.

Non-CO_2 GHG emissions comprise 18% of total developed countries' GHG emissions yet comparatively little analysis has been presented on embodied flows of these gasses. An early study by Subak (1995) estimated international flows of CH4, and Nijdam et al. (2005) calculated CO_2, CH_4, and other air pollutions embodied in international trade, but these studies did not use the more accurate global MRIO-based methods used today. Hertwich & Peters (2009) estimated CH_4 and N_2O embodied in international trade using an MRIO model but did not conduct a timeseries analysis. By constructing a time series consumption-based inventory of non-CO_2 GHGs (CH_4, N_2O, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-23, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10-mee, C_2F_6, C_3F_8, C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}, CF_4, c-C_4F_8, SF_6) it can be see that, like CO_2, developed countries have shifted their non-CO_2 GHG emissions to developing countries. Our findings indicate that burden-shifting occurs even more strongly for non-CO_2 GHG's than for CO_2.

Figure 4.2 shows this for CH_4 and N_2O emissions. The non-CO_2 emissions not only follow the CO_2 emissions trend but have more embodied emissions flowing from developing to developing countries. In 2008, 32% of the CH_4 footprint (consumption-based inventory) of developed countries came from net imports; for CO_2 that figure was just 15%. The potential of non-GHG emissions reduction in developed countries is limited because the cost to reduce non-GHG emissions was relatively cheap and the government has regulated non-GHG emissions. On the other hand, environmental regulation in developing countries is generally weaker than developed countries, and so developed countries can reduce their non-GHG footprint by mitigating emissions in developing countries or decreasing non-GHG transfer from developing to developed countries. Therefore, the finding shows non-GHG emission reduction in developing countries is promising way to reduce GHG footprint in developed countries.

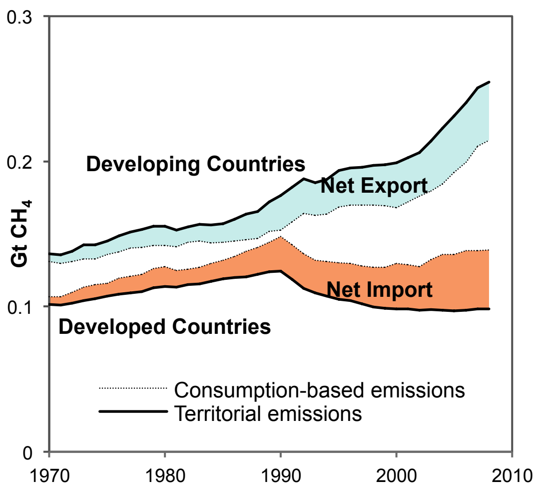


Figure 4.2a: CH_4 emissions and transfers from developing to developed countries, 1970-2008

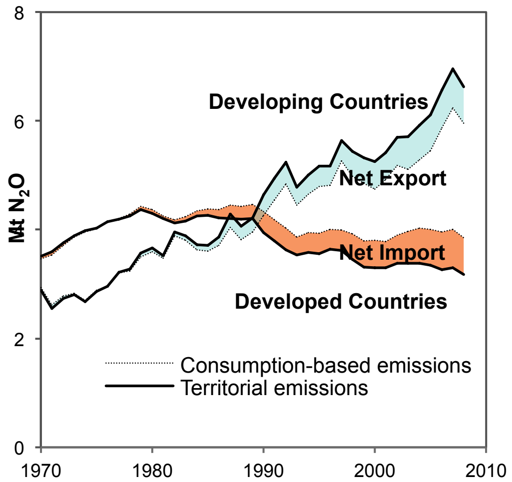


Figure 4.2b: N_2O emissions and transfers from developing to developed countries, 1970-2008

4.3.2. Burden-shifting occurs in specific sectors

Examining the sectors importing/exporting embodied emissions reveals that increased embodied emissions in net imports arrive in the same sectors that are achieving domestic reductions in developed countries. For example in the UK the Electricity, Gas, and Water sector has achieved a 16% reduction in domestic CO_2 emissions (through a combination of changing demand and increasing efficiency) since 1990, yet embodied CO_2 emissions in imports in that sector rose 208% over the same period. The result is that while territorial CO_2 emissions in that sector dropped, its total carbon footprint rose 10%. As seen in Figure 4.3 the composition of domestic reduction is closely matched, or exceeded, by increased embodied CO_2 in imports. This implies that rather than actually reducing their carbon footprint, for these sectors it has grown and moved abroad. This pattern is observed in many Annex B countries individually and for the Annex B countries collectively.

Emissions shifting manifests in several ways: new and existing emitters can relocate, a company can choose a different supplier to fulfill an order, or a decrease in domestic emissions can be more than compensated for by increased imports, as happens for example when an economy shifts from an industrial base to an information economy that increases physical imports to compensate for declining domestic production. The microeconomic decisions underlying emissions shifting are complex and energy and pollution costs are only some of the variables in businesses' decision-making. These decisions will also vary by type of industry. The embodied CO_2 used to manufacture a television or truck can easily be emitted abroad, but it is more difficult to relocate the GHG emissions needed to light a home or fuel a car. Yet whatever the precise mechanics of emissions shifting (explored by Arto & Dietzenbacher, 2012), the problem is growing.

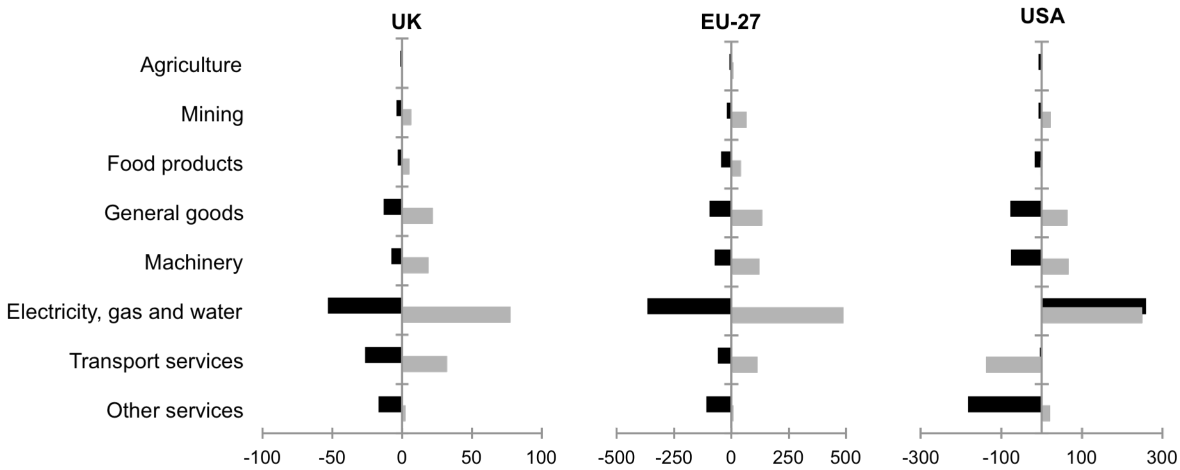


Figure 4.3: Domestic CO_2 emissions reductions (black bars) have a similar composition to the makeup of increased embodied net imports (grey bars) (in Kt CO_2). Rather than achieving reductions, for these sectors their carbon footprint has actually grown and shifted abroad. This pattern holds for most Annex B countries including the UK and the EU27 as a whole.

It is desirable to know which particular inter-country flows and supply chains are involved in burden-shifting. Mapping the top-growing bilateral flows of embodied CO_2 emissions into and out of the USA (Figure 4.4) by trade partner clearly shows a modest rise in American exports to developed countries but a large rise in imports from developing countries, particularly China and India. Embodied CO_2 flows out of China, India, Canada, Korea, Mexico, Qatar, Saudi Arabia, Indonesia, and Malaysia, and others, have grown sharply since 1990. Increases in embodied exports from the US (most substantially to China, Mexico, UK, Russia, Poland, Singapore) have been smaller. The result is a net increase in embodied imports into the US.

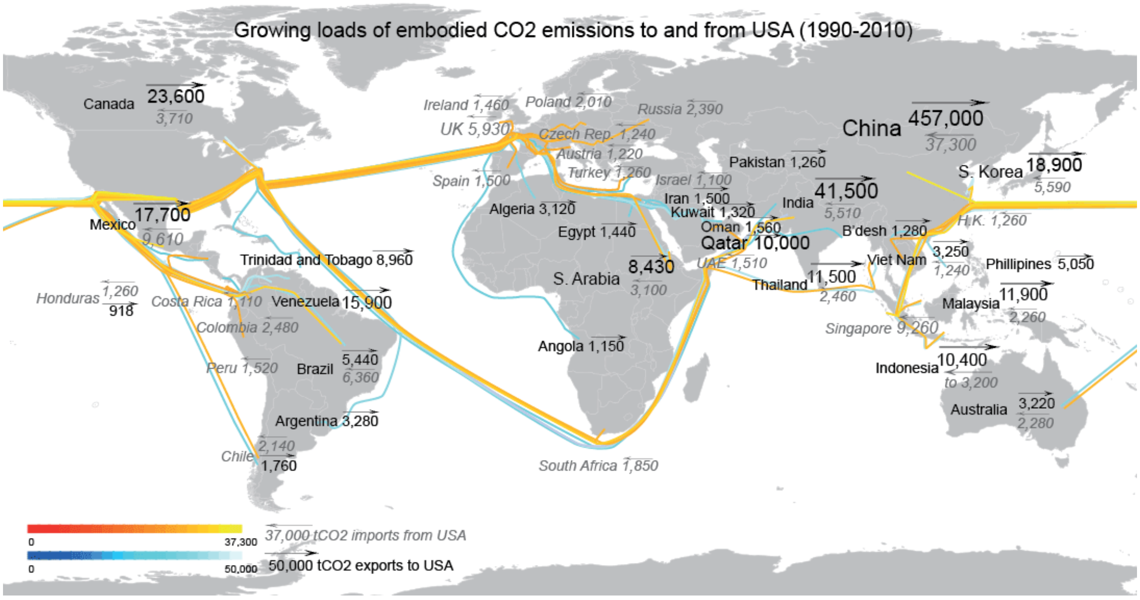
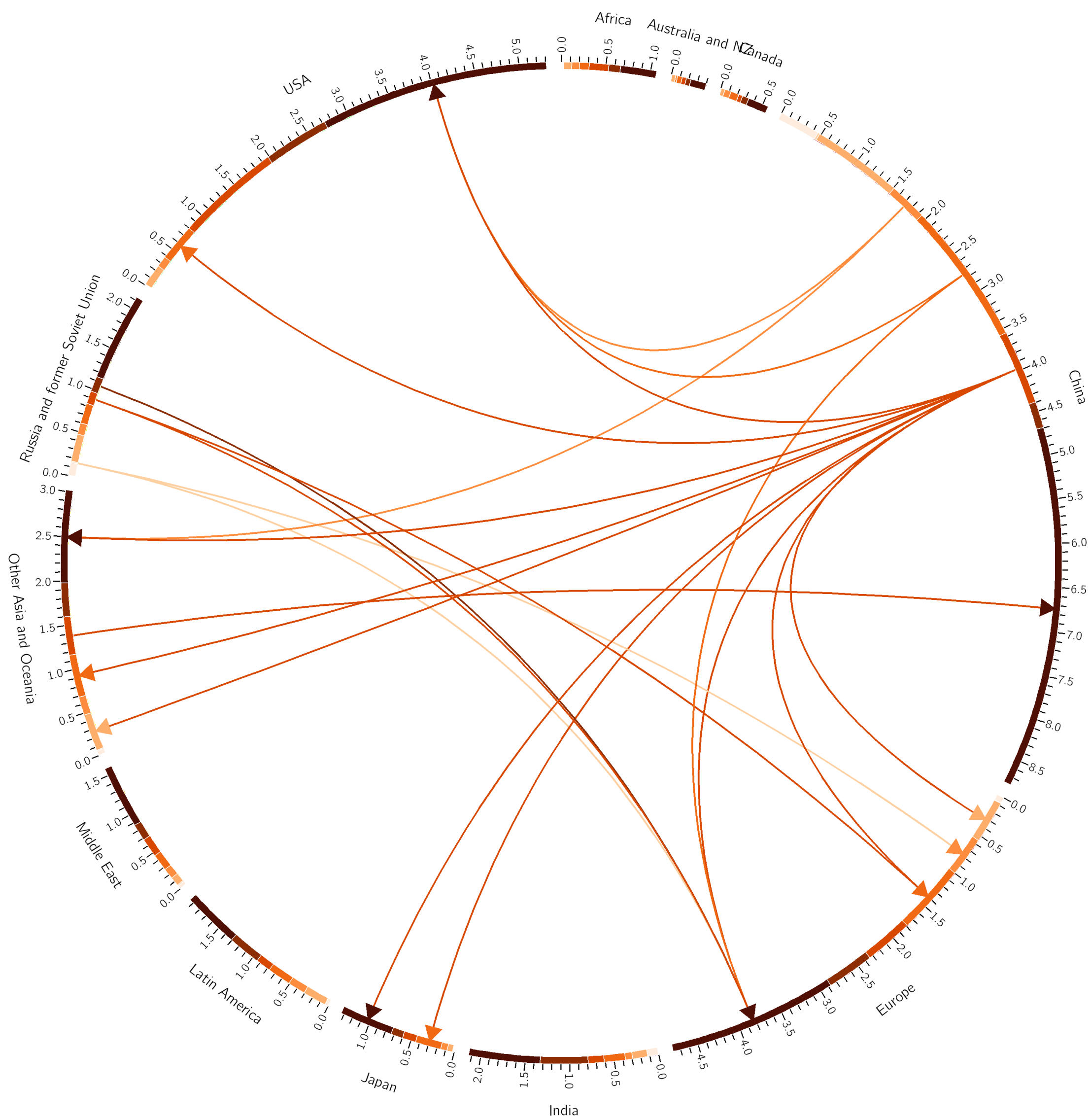


Figure 4.4: Largest growing flows of embodied CO_2 to (rightward arrows) and from (leftward arrows) the USA (absolute growth 1990-2010, in tonnes of CO_2)

Flow maps such as Figure 4.4 are useful for visualizing flows to or from individual countries. Figure 5.5 uses the Circos data visualization tool (Krzywinski et al., 2009) to find the top 20 fastest growing inter-country flows China is a major origin point of embodied emissions flows. In addition to China's contribution to emission shifting it is possible to observe some new trends. Increases in emissions in the Russian ores and minerals sectors have been driven by higher consumption in Europe. Despite considerable economic growth during the period Australia, India, and Other Asia do not originate any major growing flows. China is not just an exporter but also drives CO_2 emissions from energy production elsewhere in Asia and Oceania. This flow is likely to continue to grow because of other Asian countries' economic growth. Overall, the electricity, gas, and water sector is the dominant sector associated with territorial emissions growth and tertiary services sectors the main sectors driving this increase.



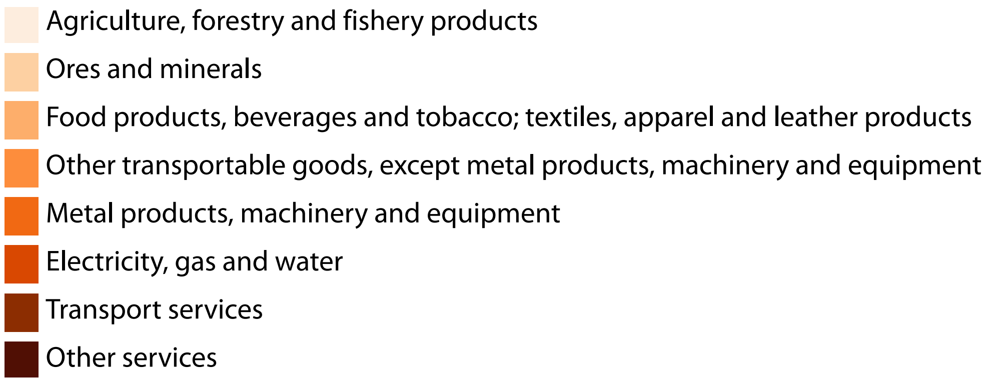


Figure 4.5: The top 20 fastest-growing inter-country CO_2 emission transfers since 1990. Arrows show embodied CO_2 flows from production sectors to final consumption sectors. Arrowhead color corresponds to final consumption sector; line color corresponds to the production sector. Each country/region arc width corresponds to its consumption-based emissions in 2011 (in Gt CO_2).

Using the methods of Structural Path Analysis (SPA) (Defourny & Thorbecke, 1984; Peters & Hertwich, 2006) it is possible to enumerate and rank the individual supply chains through which displaced emissions flow to consumers in developed countries. This analysis is done using an aggregated version of Eora in which every country uses a common 26-sector classification so that all individual supply chains are comparable, Grouping the top international supply chains experiencing the biggest growth in embodied emissions since 1990 by origin and destination it may be seen that 72% of the 200 fastest-growing paths originate outside the Annex B signatories (Table 4.1). Embodied emissions originating in Annex B countries fall within the jurisdiction of the Kyoto Protocol. Yet just 28%

of the 200 fastest-growing flows originate there. Of the 200 top fastest-growing flows, 144 originate outside Annex B countries and thus fall outside the jurisdiction of the Kyoto Protocol. If the same Kyoto signatories set targets using consumption-based emissions in addition to territorial emissions, the jurisdiction of the protocol would improve from covering 28% of the fastest-growing flows to covering 80% of the fastest-growing flows.

Flow direction	**Percentage of the 200 fastest-growing flows of embodied CO_2**
Developed countries → Developed countries	20%
Developed countries → Developing countries	8%
Developing countries → Developed countries	52%
Developing countries → Developing countries	21%

Table 4.1: Direction of fastest-growing flows of embodied CO_2 since 1990 from SPA results. 72% of the 200 fastest-growing flows originate outside Kyoto Annex B countries.

China dominates this list with 25 of the top 200 fastest-growing sectors emitting CO_2 for production bound for developed countries' consumers. In that country and others, coal and oil production, electricity generation, and transportation sectors are the large primary emitters accounting for most of the emissions shifting. Other sectors actively contributing to emissions shifting include the Chinese steel smelting, processing, and motor vehicle manufacturing industries (increased 2.5, 6.5, and 7.7 Mt), chemicals industries in Indonesia, Malaysia, South Korea, and India (increased 0.9, 1.1, 1.6, and 4.1 Mt), production of cement, electronics, paper, food, fertilizer, and plastics from Thailand, Malaysia, Indonesia, and India, and petroleum exports from Iran to India, from Qatar and Saudi Arabia to the USA, from Libya to Italy and Spain, and from Algeria to France.

Further detailed results are available in Supplementary Information (SI) S4.2.

4.4. CO_2 Follows Fleeting Air Pollution

The phenomenon of emissions shifting has already occurred with NO_x, SO_2 and PM_{10} emissions. Polluting production increasingly occurs in countries with less stringent regulation. For air pollution the result has been that despite effective regulation and technical measures (i.e. scrubbers and low-sulfur fuels) in major emitters, total global emissions have increased. A long-term time series of the air pollution footprint of nations (Figure 4.6) shows that SO_2 emissions in developed nations remained at fairly constant levels until about 1980, followed by a continuous decrease throughout the following 30 years (punctuated mainly by the 1985 Helsinki Protocol and the 1990 amendments to the US Clean Air Act). All of the European SO_x policies annotated in Figure 4.6 attempted to address transboundary pollution, though not embodied pollution within or from outside Europe. Since 1990 total SO_2 emissions in developing countries have risen 32 Mt, with 8 Mt of that increase emitted for the production of goods bound for consumers in developed countries. A similar pattern can be observed for emissions of NO_x (Figure 6). Accounting for net imports, developed countries would not have recorded a 23% NO_x reduction since 1990 but would have more or less remained at 1990 emissions levels. It must be noted that while higher pollutant emissions are generally deleterious, depending on local situations the same emission load could result a heavier or lighter societal impact. The relationship between emission and impact is complex and deserving of further study.

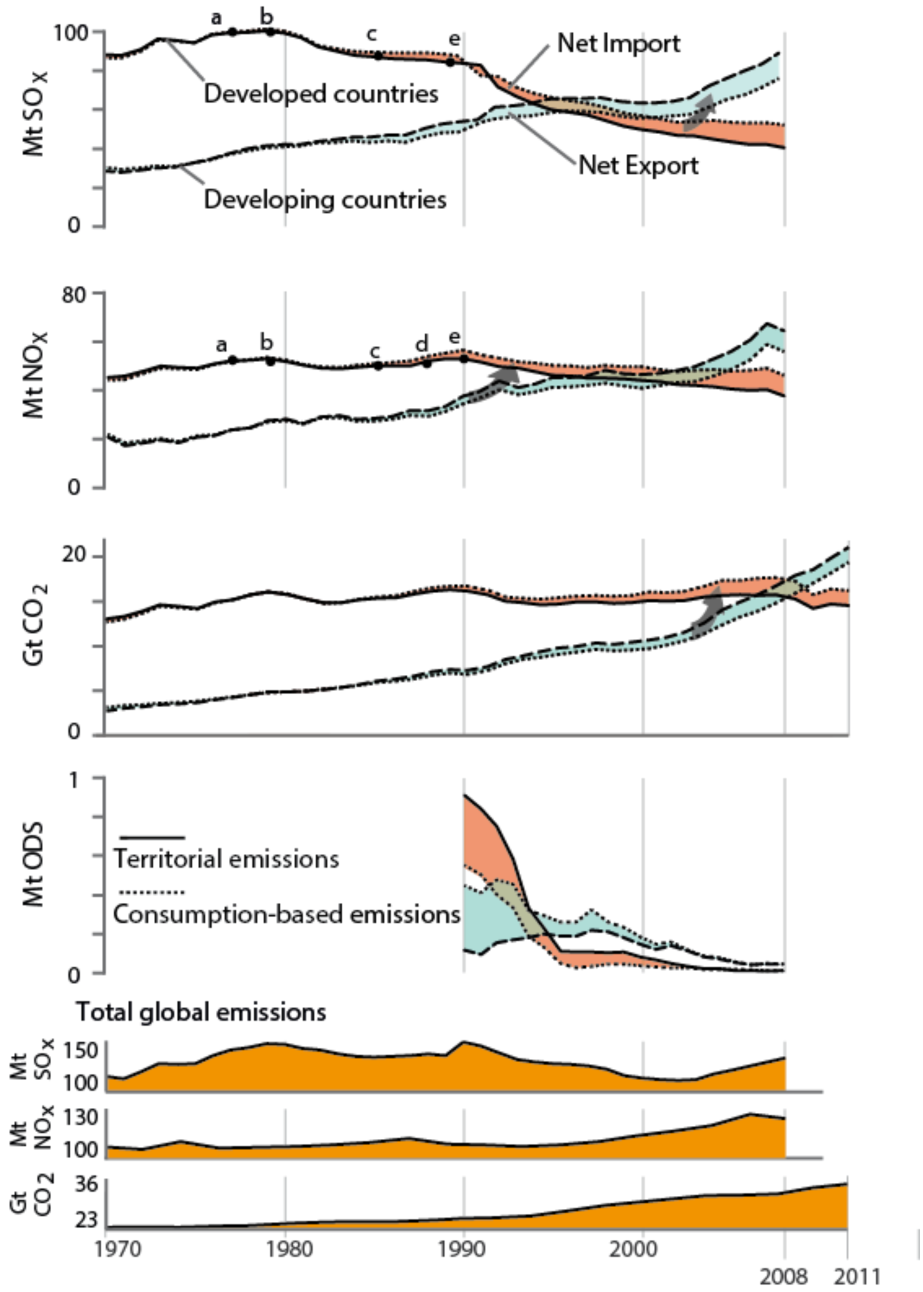


Figure 4.6: Territorial and consumption-based SO_2, NO_x, CO_2, and ODS emissions. Despite considerable regulation in the large developed economies, global emissions have increased. This increase is in part to due to shifting of embodied pollution in trade (shaded area). Major US and EU air quality regulations are annotated: (a) US Clean Air Act (CAA) 1977 Amendments (b)

1979 European Convention on Long-Range Transboundary Air Pollution (c) 1985 Helsinki Protocol (d) 1988 Sophia Protocol (e) CAA 1990 Amendments.

The historical shifting of SO_x and NO_x-intensive production to countries with weaker regulation suggests that CO_2-intensive production may similarly relocate to avoid regulation. If CO_2 emissions follow the same precedent set by air pollution emissions, it could mean global emissions continue to grow even if developed countries successfully reduce their emissions.

In contrast, the efficacy of the Montreal Protocol is clearly visible (Figure 4.6). Ratified in stages between 1987 and 1993 by 190 countries, the ban on emissions on ozone-depleting substances (ODS) and the import of products containing ODS left no safe haven to which polluters could flee. Admittedly the small volume and ready availability of substitutes made ODS a relatively easy pollutant to control, yet still the Protocol's efficacy is notable.

4.5. Conclusion

Burden shifting, originally anticipated to be a minor phenomenon, has turned out to be an important dynamic shaping global GHG emissions patterns. Using a high-resolution MRIO timeseries account of the global economy we are able to confirm earlier findings that burden-shifting is a growing problem. The efficacy of previous air pollution regulation has been undermined by burden-shifting. If GHG emissions and regulation follow this precedent there is a real risk that unless major economies recognize their imported carbon footprint even strong regulation on domestic emissions in major economies may not be effective in reducing total global emissions.

The Kyoto Protocol only regulates territorial emissions. We are not the first to propose to regulate imports and/or consumption-based emissions instead (Lenzen, Moran, Kanemoto, Foran, et al., 2012; Munksgaard & Pedersen, 2001; Peters & Hertwich, 2008a; Steckel, Kalkuhl, & Marschinski, 2010). The Montreal Protocol, the Convention on International Trade in Endangered Species and the Basel Convention are all environmental regimes that attempt to mitigate the shifting of environmental impacts by regulating both domestic activity and imports. Potential policy solutions include a carbon border tax adjustment (Atkinson et al., 2011; Helm, Hepburn, & Ruta, 2012; Hepburn, 2007; Ismer & Neuhoff, 2007), expansion of the Clean Development Mechanism (which allocates emissions abatement dollars to the most cost-efficient reduction opportunities), and setting reduction targets using consumption-based accounts. We conclude that burden-shifting is a real problem, with the fastest-growing flows of embodied emissions originating outside the jurisdiction of the Kyoto Protocol and we raise the concern that international trade may undermine pollution national emissions reduction targets.

5. Conclusion

Multi-region input-output (MRIO) analysis is emerging as a way to analyze the global supply chain (Wiedmann, 2009). There are several initiatives underway to construct global MRIO tables (Erumban et al., 2011; EXIOPOL, 2008; Lenzen, Kanemoto, et al., 2012; Peters, Andrew, et al., 2011; Timmer, 2012; Tukker et al., 2009; WIOD, 2010), and several studies using MRIO have been published in top journals recently (Davis & Caldeira, 2010; Davis et al., 2011; Lenzen et al., 2012; Peters, Marland, Le Quéré, et al., 2011; Peters, Minx, Weber, & Edenhofer, 2011b; Steinberger et al., 2012). These studies have mainly focused on global carbon footprints and consumption-based national CO_2 emissions, but there are plenty of opportunities to analyze global MRIO with other environmental and social indicators and other scales of MRIO (Lenzen, Moran, Kanemoto, Foran, et al., 2012; Nijdam et al., 2005; Weber & Matthews, 2007; Zhou & Imura, 2011).

First of all, we critically examine a number of emissions accounting concepts, examine whether the ensuing carbon balances are compatible with monetary trade balances, discuss their different interpretations, and highlight implications for policy in the second chapter. In particular, we compare the emissions embodied in bilateral trade (EEBT) method which considers total trade flows with domestic emission intensities, with the multi-region input-output

(MRIO) method which considers trade only into final consumption with global emission intensities.

Given their differences, it is worth considering which trade balance formulations would be used for different research or policy questions. If consumption-based emissions of different countries were to be compared, we would suggest an MRIO approach because of the global emissions coverage inherent in this method (Section 2.4.2). The difference between a country's territorial and consumption-based inventory (Section 2.4.1), and how it changes over time, would be a useful indicator of a country's progress towards policy objectives. However, as we showed, this difference does not have the standard properties of a monetary trade balance. Thus, care is needed to emphasize that it is a difference of inventories and not a trade balance.

If trade-adjusted emission inventories (leading to a trade balance) are to be compared, we would suggest an EEBT approach due to the consistency with a monetary trade balance (Section 2.4.3). This method is however not appropriate for consumption analysis as it does not include international supply chains. When using the EEBT method, careful framing is needed to emphasize the system boundary. Framing a policy question as, for example, "what are our territorial emissions to produce exported products" requires a territorial system boundary and hence an EEBT approach. While from an export perspective the use of EEBT may seem more intuitive, it is less intuitive when framed in terms of imports. For example, "what are the emissions to produce imported products" could imply the analysis of global supply chains and the use of the MRIO method. In both cases, careful framing of the research question and definitions is required to avoid confusion.

Through this chapter we hope that we have demonstrated some of the key issues in drawing comparisons between production, consumption, and international trade, and ideally this leads to a more consistent treatment of differences and trade balances in future studies.

In the third chapter, we have developed a time series of new environmentally extended multi-region input-output (Eora) table with applications in carbon, water and ecological footprinting, Life-Cycle Assessment (LCA), as well as trend and key driver analyses. Such applications have recently been at the forefront of global policy debates, such as about assigning responsibility for emissions embodied in internationally traded products. The new times series was constructed using advanced parallelized supercomputing resources, and significantly advances the previous state of art.

The Eora database contains annual national accounts balances for the entire period 1990-2010, for every country, in monetary terms as well as for every satellite indicator. Such balances reveal which countries are net exporters or net importers of environmental pressure. Whilst there exist several carbon, water and ecological footprint studies based on global MRIOs, these have not yet been widely utilised in LCA studies. Nevertheless, the potential for future MRIO-assisted LCA applications is large, especially when MRIO databases feature sufficiently high country and sector detail to be able to integrate with detailed bottom-up, process-specific data. The global coverage of MRIOs is particularly important given that manufacturing processes increasingly draw on raw and semi-fabricated intermediate inputs sourced from global locations with comparative cost advantages.

In conclusion, the Eora tables represent a major advance in the resolution, timeliness of multi-region input-output (MRIO) tables, and therefore also in the relevance of a wide range of applications such as carbon, water and ecological footprinting, and Life-Cycle Assessment. This advance was possible through the development of a number of innovations such as a data processing language, new optimisation algorithms, advanced computational solutions, and the simultaneous construction of uncertainty estimates.

In the fourth chapter, we investigate emission leakage caused by Kyoto Protocol. Many developed countries in Annex B of the Kyoto Protocol have been able to report decreasing emissions, and some have officially fulfilled their CO_2 reduction commitments. This is in part because current reporting and regulatory regimes allow these countries to displace emissions intensive production offshore. Using a new highly detailed account of emissions embodied in international trade we investigate this phenomenon of emissions leakage.

In this chapter we present several new findings. First, we are able to independently confirm previous findings that adjusting for trade, developed countries emissions have increased, not decreased. Independent confirmation of this result is important given the prominence of consumption-based accounting in setting national and international GHG reduction targets. Our inventories also consider non-CO_2 GHGs, and we confirm the burden-shifting effect is similar, or stronger, for these gasses. Second, we find that the sectors successfully holding or lowering their domestic emissions are the often the same as those increasing their imports of embodied CO_2. This suggests that it is not cleaner production or consumption patterns that are reducing domestic emissions, but simply burden-shifting of the same emissions-intensive activities. Third, we find that 72% of the 200 fastest-growing flows of embodied CO_2 originate outside the Kyoto Annex B signatory nations. These fastest growing flows transport embodied emissions from developing countries both to developed and other developing countries. Finally, we find that historically the same phenomenon of emissions displacement has already occurred for air pollution. The result has been that despite aggressive legislation of SO_x, NO_x and PM_{10} in major emitters, total global air pollution emissions have increased. We conclude that burden-shifting is a real problem, with the fastest-growing flows of embodied emissions originating outside the jurisdiction of the Kyoto Protocol and we raise the concern that international trade may undermine pollution national emissions reduction targets.

In terms of climate policy participation from developing countries and reduction of the impact of international trade on climate are the issues for

Post-Kyoto Protocol negotiation (Peters & Hertwich, 2008b) Consumption-based GHG emission has been widely viewed as promising way to proceed to negotiation (e.g. Peters & Hertwich, 2008a). However, the policy-maker required well-established accounting methods and consumption-based emissions with low-uncertainty to the researchers. We established accounting frameworks for sales-based and consumption-based inventory in Chapter 2. The inventories should not delay more than few years because the governments refer to the inventory for policy making. We established the Eora MRIO method and system that is provided to the policy-makers in 1-2 years prior to current year in chapter 3. Consumption-based emissions should be comparable to current UNFCCC territorial emissions, but existing literatures have not provided timeseies consumption-based non-CO_2 greenhouse gases. In addition to consumption-based CO_2 emissions, we have firstly estimated timeseies consumption-based non-CO_2 greenhouse gases in Chapter 4.

Our findings showed in this dissertation improve our understanding of theoretical and applied multi-region input-output economics and footprint accountings, and we discuss the policy implications derived from the findings. We have only just begun MRIO analysis. A lot of MRIO applications will be conducted using Eora and other MRIO tables.

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Appendix for

World trade and the environment: Essays on economic structure, international supply chains, and environmental impact

Keiichiro Kanemoto

Text S3 *Appendix for* Mapping the structure of the world economy

Text S3.1 Extended Multi-region input-output tables and analysis

Thanks to Leontief's innovation and to governance by the United Nations (Commission of the European Communities, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank, 1993), every input-output table conforms to a standardized structure (Fig. S3.1). Producing entities (so-called *sectors*) are listed along rows and columns in a symmetrical fashion, and every element in the table holds a number that describes the monetary value of a transaction between the row sector supplying a product to the column sector that uses it. Sectors are usually aggregates over many industrial establishments, for example wheat growing, iron ore mining, steel manufacturing, electricity generation, road transport, or banking services. An input-output table holds in its columns the inputs, or the *production recipe*, and in its rows the *sales structure* of all sectors. In its entirety, it contains complete information on the internal interdependence, or structure, of an economy.

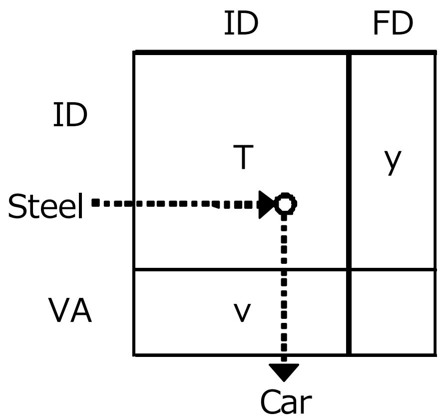


Figure S3.1a: Schematic of an input-output table. ID = Intermediate demand, matrix **T**; FD = Final demand, matrix **y**; VA = Value Add (sometimes called Primary Inputs), matrix **v**.

In accordance with the standards set in the United Nations' System of National Accounts (Commission of the European Communities et al., 1993), input-output tables make a distinction between primary and intermediate inputs, and intermediate and final outputs. *Intermediate inputs and outputs* (matrix **T** in Fig. S3.1a) are supplied and used by producers of goods and services, that is companies and the public sector. However, in order to operate, each producer also needs inputs from non-producing entities, for example labour or capital, and such inputs are included in the *primary inputs* block (matrix **v**). Finally, each producer not only supplies other producers, but also final consumers such as households, and such outputs are contained in the *final demand* block (matrix **y**).

In addition, the United Nations guidelines (United Nations, European Comission, International Monetary Fund, Organization for Economic Co-operation and Development, & World Bank, 2003) provide for an integration of the monetary input-output tables with so-called *satellite accounts* that hold additional information for example on the use of natural resources such as water or energy, on pollution such as emissions, or on other physical inputs into production such as human labour. Satellite accounts are constructed in the same sector classification as the monetary account, and then simply appended to input-output tables.

The System of National Accounts also provides for an input-output table variant called a supply-use table, where the concept of producing sectors is refined into two concepts: an *industry*, and the *products* that it produces. The difference between the sector perspective and the industry-product perspective is that the latter allows one industry to produce more than one product, and one product to be produced by more than one industry. This enhanced detail in a supply-use table is captured in two separate matrices called the *use* matrix (**T**) and the supply matrix (**V**, see Fig. S3.1b).

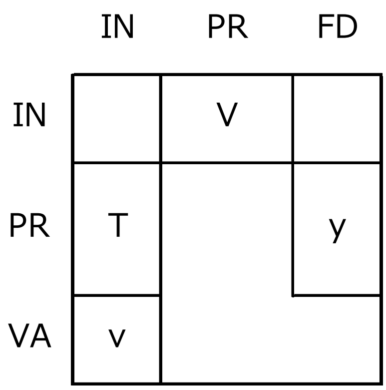


Figure S3.1b: Schematic of a supply-use table. ID = Intermediate demand, matrices **T** and **V**; FD = Final demand, matrix **y**; PI = Primary inputs, matrix **v**; IN = Industries, PR = Products.

The System of National Accounts also defines three different valuations at which input-output transactions can be expressed: basic prices, producers' prices, and purchasers' prices. Basic prices refer to the factory- or farm-gate value of a product, whereas producers' and purchasers' prices include various mark-ups such as transport and trade margins, taxes, and subsidies. A full set of input-output tables may include many tables that assume the shapes shown in Figs. S3.1a and S3.1b, but contain different types of mark-ups. In unison, the three basic blocks expressed at basic prices as well as various valuations, provide an exhaustive picture of all money flows in an economy.

Input-output tables are used for input-output analysis, a versatile macroeconomic technique that is used in an enormously diverse range of applications, ranging from economic policy modelling, logistics and scheduling, key sector identification, environmental footprinting, structural decomposition, and life-cycle assessment (Miller & Blair, 2009; Rose & Miernyk, 1989). The unique feature of input-output analysis is that it uses the information on the interdependence of economic sectors in order to quantify complex, indirect repercussions, originating as a result of an initial economic activity, and then travelling along a vast supply-chain network. This capability is embodied in the famous inverse matrix conceived by Leontief l(Leontief, 1970). Well-known examples are carbon footprints that include the emissions consequences of all indirect supply-chain transactions resulting out of a single purchasing decision.

In a single-region input-output table, primary inputs include imports, and final demand includes exports. This is because in the context of a single region, foreign agents are not in intermediate, but at the extreme positions of supply chains. One input-output table variant that was already devised by Leontief (Leontief & Strout, 1963), but has only experienced intensive research and major breakthroughs throughout the past decade, are multi-region input-output (MRIO) tables. In essence, an MRIO table links many single-region input-output tables into one consistent account of intra-regional and inter-regional trade (Fig. S3.1c).

Today, MRIO tables exist at the sub-national as well as the international level.

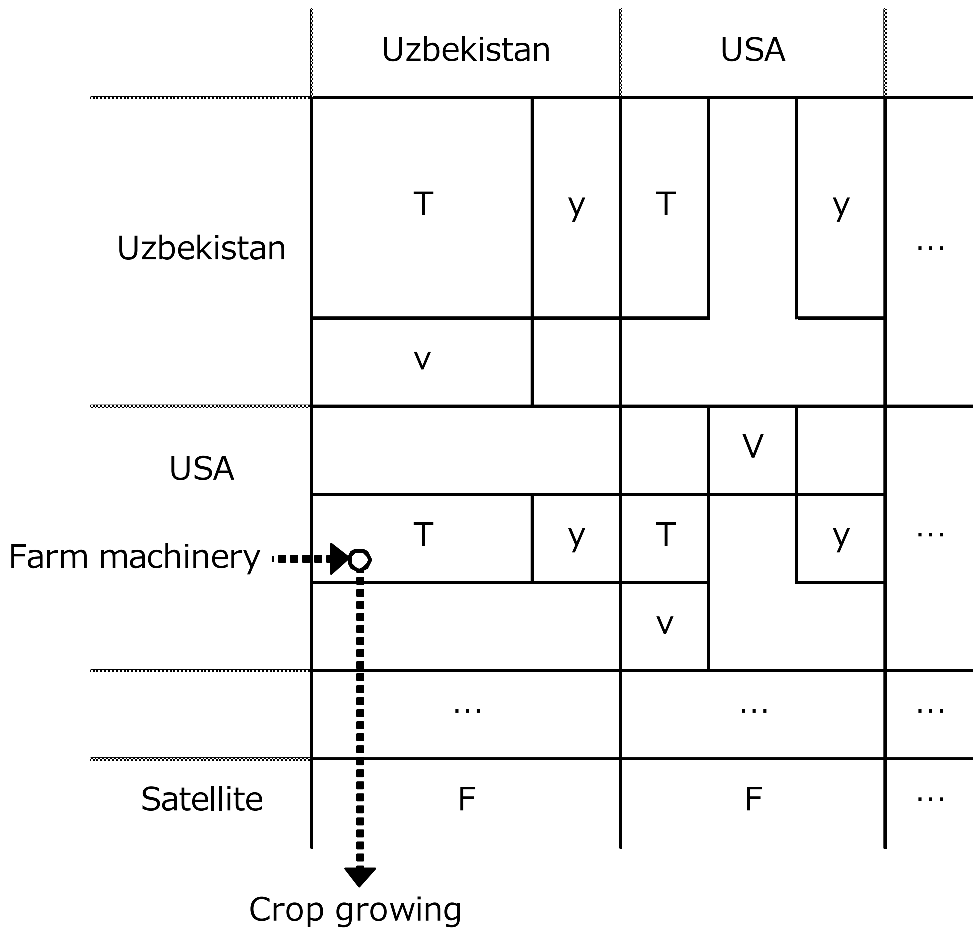


Figure S3.1c: Schematic of a 2-country section within an environmentally-extended multi-region input-output table, for the example of r = USA (supply-use table), and s = Uzbekistan (input-output table). ID = Intermediate demand, matrices **T** and **V**; FD = Final demand, matrix **y**; PI = Primary inputs, matrix **v**; IN = Industries, PR = Products.

When applied to MRIO tables, input-output analysis is more powerful than in single-region applications, simply because the MRIO database underlying the analytical techniques offers information on national production recipes as well as international trade relationships. This constitutes the main motivation behind developing ever-more detailed, ever-larger MRIO tables, and in particular the reason for developing the Eora MRIO database.

Text S3.2 Balancing and time series iteration

In the following we will denote MRIO table components for the year y in valuation v by $MRIO_{ij,y}^{rs(v)}$, where $MRIO = \mathbf{T}$ (domestic input-output, use, or trade), $\mathbf{y}$ (final demand excluding exports), $\mathbf{v}$ (value added), $\mathbf{V}$ (supply tables), aggregate exports $\mathbf{e}$, aggregate imports $\mathbf{m}$, or imports matrices $\mathbf{M}$ (for intermediate use) and $\mathbf{N}$ (for final demand), indexed by exporting country r, importing country s, supplying sector i, and demanding sector j. We derive gross output $\mathbf{x} = \mathbf{T1} + \mathbf{y} + \mathbf{e}$, where $\mathbf{1}$ is a summation vector. The symbols $\mathbf{e}$ and $\mathbf{m}$ are used instead of $\mathbf{T}^{rs,r\neq s}$ when we refer explicitly to exports or imports statistics. Sectors can be industries as well as commodities, depending on whether countries are represented by IIOT, CIOT or SUT. Sectors can also be value-added and final demand categories. A dot $\cdot$ is used to denote summation over the replaced index instead of using the summation sign $\mathbf{S}$. A circle ° next to another index is used to denote summation over the replaced index, but excluding the adjacent index. We will denote valuation alternatively by script (pu – purchasers' price, pr – producers' price, ba – basic price, mn – margin n, tx – tax, sb – subsidy) or numeric indices. We will leave out the year index y wherever it is not needed.

The time series is constructed iteratively, by starting with the 2000 initial estimate (chosen because this year provides the best overall availability of national input-output tables, per *SI Appendix*, Table S3.3), reconciling this with all 2000 constraints, and taking the solution as the initial estimate for 2001, and so on. Back-casting to 1990 proceeds similarly. A balanced table for one year will be an inappropriate initial estimate for the next year under strong economic growth. Therefore, we have constructed initial estimates by scaling all prior solutions with inter-year ratios $ß^{rs}_{\mathbf{T,y,v,V}}$ specific to transactions (use, trade) $\mathbf{T}$, final demand $\mathbf{y}$, value added $\mathbf{v}$, and supply tables $\mathbf{V}$. These ratios were derived from country time series data on GDP, exports, imports, and value added (United Nations Statistics Division, 2011a).

Balanced MRIO tables were obtained by specifying an initial estimate (vectorized as $\mathbf{a}_0$), and applying the quadratic programming approach by van der Ploeg (1988). Here, external constraint information $\mathbf{c}$ (often called "superior data") are linear functions $\mathbf{c} = \mathbf{C}\ \mathbf{a} + \mathbf{e}$ of the vectorized MRIO entries $\mathbf{a}$, as well as disturbances $\mathbf{e}$ that describe the constraint violation. We chose this approach because the disturbances allow effective handling of disparate, unaligned, conflicting and unreliable information (Lenzen, Gallego, & Wood, 2006, 2009), and because signs and zeros are not necessarily preserved. The sign- and zero-preservation inherent in the variants of the RAS balancing method is undesirable because it does not allow account items such as net taxes and changes in inventories to switch signs, and it forces all variables connected to zero-valued constraints to zero without compromise.

van der Ploeg extends $\mathbf{a}$ with the disturbances $\mathbf{e}$, to a compound unknown $\mathbf{p}$, distributed as

$$\mathbf{p} = \begin{pmatrix} \mathbf{a} \\ \boldsymbol{\varepsilon} \end{pmatrix} \sim \mathrm{D}\left[\begin{pmatrix} \mathbf{a}_0 \\ 0 \end{pmatrix}, \begin{pmatrix} \boldsymbol{\Sigma}_a & \\ & \boldsymbol{\Sigma}_c \end{pmatrix}\right] = \mathrm{D}[\mathbf{p}_0, \boldsymbol{\Sigma}] \tag{S1}$$

with mean $\mathbf{p}_0 = [\mathbf{a}_0 \mid 0]$, and variance $\mathbf{S} = [\mathbf{S}_a \mid \mathbf{S}_c]$. Exactly known constraints are a special case with the corresponding element in $\mathbf{S}_c$ being zero. Extending $\mathbf{G} = [\mathbf{C} \mid -\mathbf{I}]$, where $\mathbf{I}$ is the unity matrix, and assuming that all covariance terms in $\mathbf{S}$ vanish, the generalised optimisation problem becomes

Minimise $f\,(\mathbf{p},\ \mathbf{p}_0,\ \mathbf{S})$ subject to $\mathbf{G}\ \mathbf{p} = \mathbf{c}$. (S2)

Text S3.2.1 Quadratic Programming approaches

One approach that has been used to reconcile large input-output tables and Social Accounting Matrices is Quadrat Programming (van der Ploeg, 1988). Here the objective function is $f\,(\mathbf{p},\ \mathbf{p}_0) = (\mathbf{p} - \mathbf{p}_0)'\ \hat{\mathbf{\Sigma}}^{-1}\ (\mathbf{p} - \mathbf{p}_0)$. Setting up the Langrangean as $L = (\mathbf{p} - \mathbf{p}_0)'\ \hat{\mathbf{\Sigma}}^{-1}\ (\mathbf{p} - \mathbf{p}_0) + \mathbf{l}(\mathbf{Gp} - \mathbf{c})$, solving the first-order condition leads to analytical solutions $\mathbf{l} = (\mathbf{G}\,\hat{\mathbf{\Sigma}}\,\mathbf{G}')^{-1}(\mathbf{Gp;}_0 - \mathbf{c})$ and $\mathbf{p} = \mathbf{p}_0 - \ \hat{\mathbf{\Sigma}}\,\mathbf{Gl}$, however these do not guarantee any non-negativity that might need to be imposed on some elements. We therefore add inequality constraints $l_i \leqslant p_i \leqslant u_i$ forcing the solution to lie within lower and upper bounds $l_i,\ u_i \in [-\infty,+\infty]$. These lower and upper bounds result from definitions of accounting variables. For example, the bounds for changes in inventories are $[-\infty,+\infty]$, those for subsidies are $[-\infty,0]$, and those for remaining MRIO elements are are $[0,+\infty]$.

The mixing of equality and inequality conditions precludes analytical solution, and requires sophisticated numerical solvers. Several commercial solvers were tested during Eora's development phase. Most commercially available solvers such as CPLEX are designed to operate on a single processor leading to unacceptably long runtimes for the reconciliation of the Eora tables. We then focused on parallel optimisation and found that most parallel solvers such as PGAPack or PARAGenesis (which both apply the genetic algorithm) are not applicable to the reconciliation problem of the Eora tables. The GAMS modelling system (available at http://www.gams.com/), which is also popular for MRIO reconciliation, offers an optimiser that is not parallelisable. XPRESS (available at http://www.fico.com/) offers a parallel optimisation suite for a number of optimisation approaches such as linear programming, mixed-integer programming or quadratic programming. However, the large number of variables within the Eora tables exceeds the design boundaries of XPRESS by a factor of 1000. A parallel version of CPLEX is available for linear and quadratic programming. However, for linear programs, the problem is solved using different solvers in parallel (see http://www-01.ibm.com/support/docview.wss?uid=swg21400049). Each individual solver is executed serially on a single processor. The parallelization therefore doesn't gain any speed-ups for the individual solvers offered by CPLEX. Detailed explanation on the parallelization of the CPLEX solver for quadratic programming is currently not provided on the CPLEX website (see http://www.aimms.com/features/solvers/cplex). However, at the time of writing CPLEX only supported linear constraints for quadratic programming, but not boundary constraints. Hence, CPLEX's quadratic programming solver could not be applied to Eora's particular optimization problem. During the earlier development of Aisha, a distributed-memory-type parallelisation of CPLEX using MPI was investigated. This approach proved to be unsuccessful because the communication overhead caused by the exchange of data between the different computing nodes eliminated any computational speedups obtained through multi-core parallelisation. A good overview of available optimisation packages is available at http://www.mat.univie.ac.at/~neum/glopt/software_g.html.

As a result of the unavailability of commercial solvers, we resorted to writing tailored QP solvers. At the time of writing, the AISHA tool offers two optimisation algorithms to solve van der Ploeg's generalised optimisation problem for a quadratic objective function. The first one is a QP method described by Huang et al. (2008), the second one is based on Cimmino's Algorithm (Zenios & Censor, 1997).

Text S3.2.2 RAS variants

AISHA also offers a RAS-type optimisation algorithm called KRAS (Lenzen et al., 2009), which is an extension of RAS that can be applied to RAS-type problems such as the one given in Equation S2, where the objective function is

$$f(\mathbf{p}, \mathbf{p}_0) = \sum_j^N p_j \ln\left(\frac{p_j}{e p_{0,j}}\right).$$

Let j be the counter over the elements of $\mathbf{p}$ and the columns of $\mathbf{G}$, let i be the counter over the rows of $\mathbf{G}$, and let n be the current iteration step. Let N be the total number of elements in $\mathbf{p}$ and let M be the total number of constraints (which is equal to the number of rows in $\mathbf{G}$). Let λ_i denote the Lagrange-multipliers. Setting up a Langrangean as

$$\mathcal{L} = \sum_{j;p_j \geq 0} p_j \ln\left(\frac{p_j}{e p_{0,j}}\right) + \sum_{j;p_j<0} p_j \ln\left(\frac{p_j}{e p_{0,j}}\right) + \sum_i \lambda_i \left[\sum_j g_{ij}\, p_j - c_i\right]$$

and solving the first-order condition leads either to either an iterative Gauss-Seidel-type adjustment scheme (GRAS variant) given by

$$r^{(n)} = \frac{c_i + \sqrt{c_i^2 + 4 \sum_{j,p_j^{(n-1)} g_{ij}>0} g_{ij} p_j^{(n-1)} \sum_{j,p_j^{(n-1)} g_{ij}>0} g_{ij} p_j^{(n-1)}}}{2 \sum_{j,p_j^{(n-1)} g_{ij}>0} g_{ij} p_j^{(n-1)}}$$

and

$$p_j^{(n)} = p_j^{(n)} \left[r^{(n)}\right]^{\operatorname{sgn}\left(p_j^{(n-1)} g_{ij}\right)}$$

with $i = n \bmod M$, or (via Bregman's method; KRAS variant) to an updating condition

$$\lambda_i^{(n)} = \begin{array}{c} \text{use the solution of Eqn (S3) for } i = n \bmod M \\ \lambda_i^{(n-1)}, \text{for } i \neq n \bmod M \end{array}$$

that requires solving a generalised polynomial

$$P_i\left(\lambda_i^{(n)}\right) = \sum_{j;p_j \geq 0} g_{ij} p_j^{(n-1)} r_i^{(n)^{-g_{ij}}} + \sum_{j;p_j < 0} g_{ij} p_j^{(n-1)} r_i^{(n)^{g_{ij}}}. \tag{S3}$$

The main difference between KRAS and other RAS variants is that KRAS can handle conflicting constraints, by considering the provided reliability information during the optimisation process. Additionally KRAS is parallelisable, and can also handle sign flips and inequality constraints $l_i \leqslant p_i \leqslant u_i$. In comparison to QP algorithms, the coding of RAS variants is less complex, and their execution requires less RAM.

Text S3.2.3 Comparison of optimisation objectives

As shown in the two preceding sections, the reconciliation of an MRIO can be approached using different methods. The most common approaches are RAS-type methods, linear programming techniques and quadratic approaches such as van der Ploeg's least-square method. Each approach can be motivated, and all of them have precedents within IO research and applications (Huang et al., 2008). However, obviously, each approach yields a different result. The magnitude of the differences between various methods depends highly on the nature of the constraints and the feasibility of the optimization problem. The more the initial estimate has the be adjusted by the optimisation routine in order to adhere to the externally given constraints, the more the results of various methods will differ from one another. Consider the 2-dimensional problem

$$\text{Minimise } f\left(\begin{pmatrix} p_1 \\ p_2 \end{pmatrix}, \begin{pmatrix} 1 \\ 3 \end{pmatrix}\right) \text{ subject to } \begin{pmatrix} 1 & -2 \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = 0.$$

Hence, in this case we have

$$\mathbf{G} = \begin{pmatrix} 1 & -2 \end{pmatrix}, \mathbf{p}_0 = \begin{pmatrix} 1 \\ 3 \end{pmatrix}, \text{and } \mathbf{p} = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix}.$$

The feasible set defined by $\mathbf{Gp} = 0$ are the points that lie on the blue line within the graph. The different objective functions for this example are:

$$f_{\text{RAS-type}} = \sum_{j=1}^{2} p_j \ln\left(\frac{p_j}{e p_{0,j}}\right)$$

$$f_{\text{linear}} = \sum_{j=1}^{2} \left|p_j - p_{0,j}\right|$$

$$f_{\text{quadratic}} = \sqrt{\sum_{j=1}^{2} \left(p_j - p_{0,j}\right)^2}.$$

The constraints equation $(1 \ -2)\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = 0$ can be used to express p_2 as a function of p_1 for the feasible set. We have

$$(1 \ -2)\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = 0$$

$$\Leftrightarrow p_1 - 2p_2 = 0$$

$$\Leftrightarrow \ p_2 = \frac{1}{2} p_1.$$

With this formulation we can express the objective functions as functions of the single variable p_1 on the feasible set $\mathbf{Gp} = 0$ (Fig S3.2a).

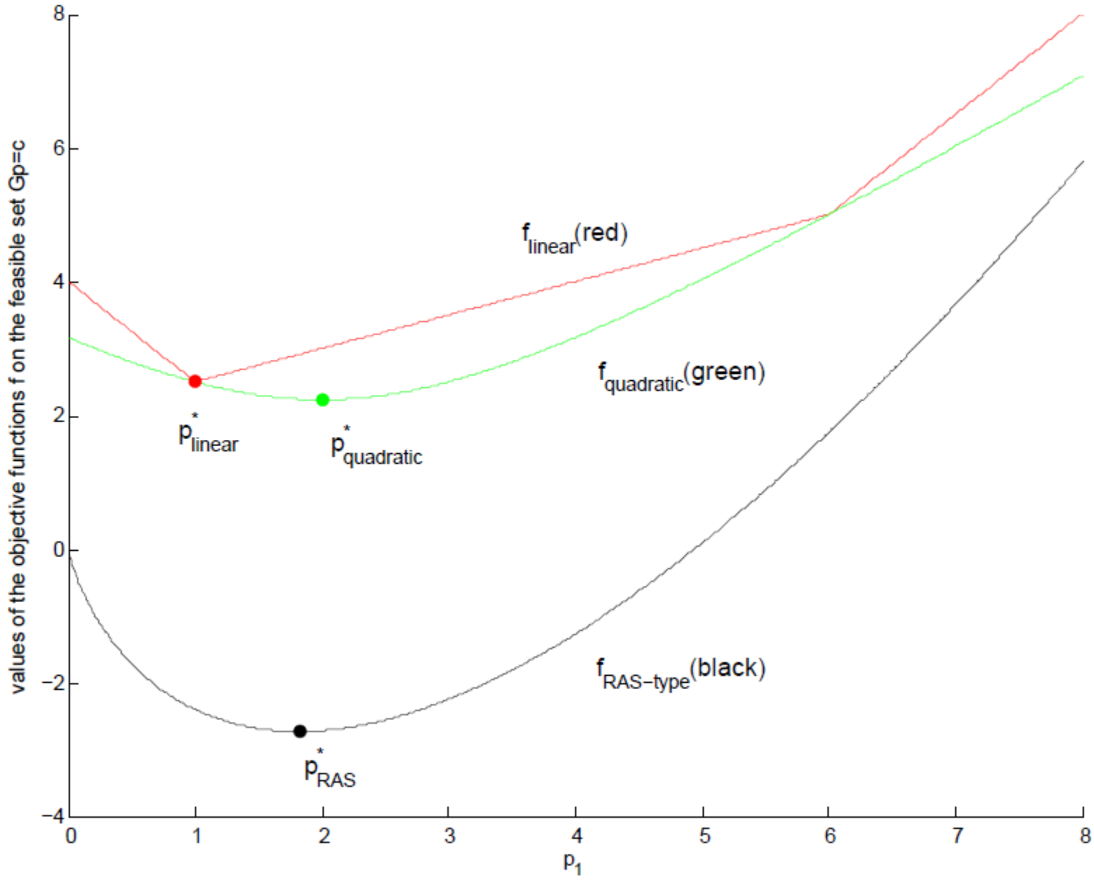


Fig S3.2a: Visualization of the values of the three different objective functions on the feasible set defined by $\mathbf{Gp} = 0$ as functions of p_1. All three objective functions have their unique minima, however these are different from one another. The values of the objective functions do not give any indication whether a particular objective function is more suitable for the 2-dimensional problem than others.

We observe that the p_1 values for optimal solutions of the different objective functions are different. The optimal p_1 values can be used to calculate corresponding p_2 values to find the solutions on the feasible set given by $\mathbf{Gp} = 0$. Fig S3.2a shows the three different solutions together with the feasible set and the initial estimate in the p_1/p_2 plane.

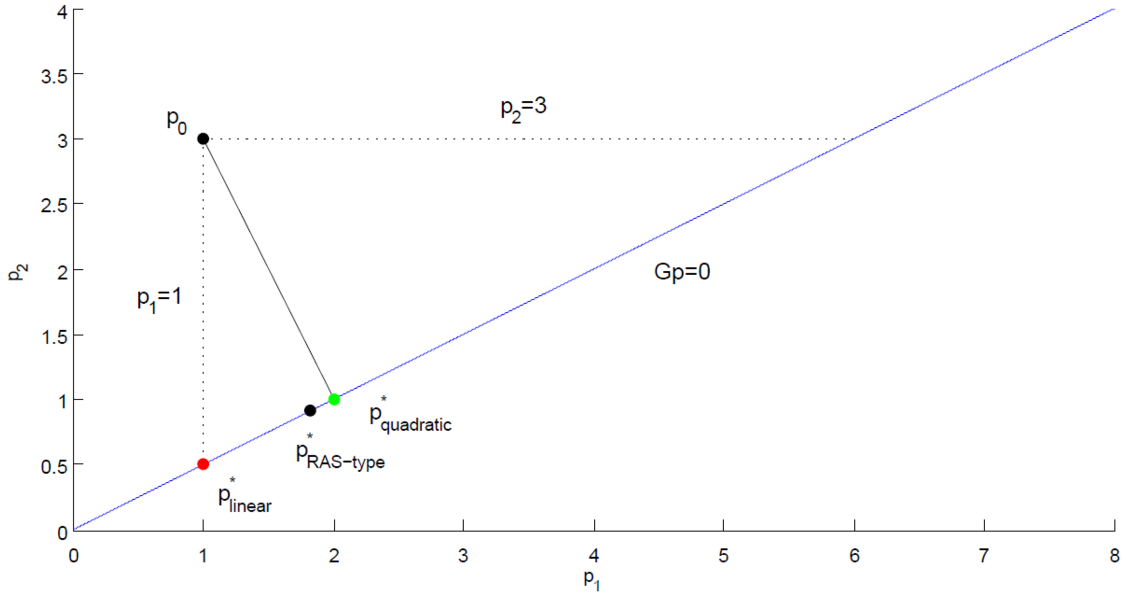


Fig S3.2b: Visualization of the different solutions of the 2-dimensional problem posed above, for different optimization methods. The blue line represents the set of feasible points defined by the equation $\mathbf{Gp} = 0$, $\mathbf{p}_0$ is the initial estimate. The colors for the solutions of the different approaches are the same as in plot Fig S3.2a: The red dot represents the solution for the linear approach, the black dot on the blue line for the RAS-type approach, and the green dot for the quadratic programming method. The line connecting the initial estimate and the result of the quadratic approach is perpendicular to the set of feasible points, and hence intuitively the "shortest" distance.

The solution to the quadratic approach is usually the one that we will interpret as the "best" solution, because it is the point "closest" to the blue line in a Euclidean sense. Also, only the quadratic approach yields the solution that represents the minimal absolute distance between the initial estimate and $\mathbf{p}_0$ the blue line.

The solution for the linear programming approach has a similar yet slightly less intuitive explanation. A linear programming approach uses a so-called

$\ell 1$-type norm to measure the distance between two points. For this 2-dimensional example, the $\ell 1$-norm only allows the movement along the grid lines of the 2-dimensional plane when measuring the distance between two points. The distance between the initial estimate and any point on the blue line is measured by adding the distance in p_1–direction and the distance in p_2–direction. In this problem, the minimal distance in a $\ell 1$-norm sense is achieved if the point on the blue line and the initial estimate have the same p_1–coordinate. That way, no additional distance into the p_2–direction has to be added to the $\ell 1$-norm of the distance between the points. Another popular example to motivate the $\ell 1$-norm is that of a taxi driver in Manhattan (see http://en.wikipedia.org/wiki/Taxicab_geometry): If we consider that Manhattan's streets are made up by a perfect grid of streets in North-South direction and by streets in East-West direction, then a taxi driver who wants to driver between two arbitrary intersections within the grid has to measure the distance between those intersection by adding up the distances that he has to travel in North-South direction and in East-West direction. This is exactly the $\ell 1$-norm between the two intersections. The taxi driver cannot travel the direct way between the two intersections (which would measure the distance between the two intersections in the $\ell 2$-norm), as this might require travelling diagonally through the grid, which is obviously impossible.

RAS-type functions do not measure an intuitive distance between different points within a space, but an information loss that occurs when moving from one point to the other. Bacharach (Bacharach, 1970) goes into great detail motivating this information loss interpretation of the RAS objective function.

Text S3.2.4 Innovative solutions in workflow management, optimisation algorithms, and computer hardware

In order to assemble and balance MRIO tables at such a large scale, a host of obstacles had to be overcome by developing a number of innovative features. First, the multitude of disparate, incomplete, and misaligned data were integrated using a custom-built data processing data processing tool called AISHA, which handles data reading, alignment and re-classification, as well as the construction of the optimisation problem and inter-year handover, in one streamlined *pre- and post-processing workflow* (Geschke, Lenzen, Kanemoto, & Moran, 2011; Yu, Lenzen, Dey, & Badcock, 2009). The AISHA programming language (A-LANG) allows the user to efficiently define sets of similarly structured constraints (such as balancing constraints) on the data set in as single command lines. Constraints of arbitrary shape or complexity can be defined using A-LANG. A-LANG enables one person to define from scratch, within a few weeks, the approximately 4 million A-LANG commands that are necessary for each year of the time series. For each input data source one or more A-LANG expressions are created in order to specify which parts in the MRIO are addressed by the data. AISHA's language interpreter then processes these scripts, reading data files, and applying concordance matrices as required. AISHA automatically vectorizes the entire MRIO initial estimate $\mathbf{p}_0$, the raw data $\mathbf{c}$, the standard deviations $\mathbf{s}$, interprets the A-LANG commands, and transforms A-LANG command lines into one or more rows of the constraints matrix $\mathbf{G}$. Thus, AISHA automates the time-consuming and complex process of constructing the entire constrained optimization problem $\{\mathbf{G}, \mathbf{p}, \mathbf{c}, \mathbf{s}\}$, and configure it so it can be fed into the optimizer.

Second, we had to deal with two problems related to the *optimiser*. To start with, as explained in Section 3.2.2, the abundance of conflict in existing raw data prevents conventional IO table balancing methods such as RAS and GRAS from converging, requiring more sophisticated optimisation approaches such as Quadratic Programming (van der Ploeg, 1988). However, variable spaces in excess of 1 billion are beyond the capability of commercially available QP optimisation software (see *SI Appendix*, Texts S3.2.1-3.2.3). We therefore developed a novel optimisation algorithm that resolves data conflicts and produces a balanced MRIO table (Lenzen et al., 2009). This algorithm is called by AISHA between pre- and postprocessing.

Third, we invested significant effort into developing *parallelized algorithms* for shared-memory computer architectures in order to construct, balance, and reconcile raw data within acceptable runtimes. At present, building the 20-year Eora time series takes approximately 2.5 weeks to complete. The Eora build-pipeline is computationally intensive: peak RAM use is $>$250 GB, and the entire system runs on a computing cluster with 72 cores, 600 GB of RAM, and 13 TB of storage. Because the Eora MRIO transactions matrix T is a large matrix ($\approx$9 GB, with 5 price sheets stored at double floating point precision) and many computations require several working copies of the matrix, Eora is RAM-intensive. The optimizer in particular is especially RAM intensive as it must also access the $\approx$40 GB constraints matrix G described above. CPU power is important to perform linear algebra quickly. And fast storage is important as the Eora build pipeline uses many temporary files. It is generally possible to trade off between time and space, caching results or using larger-RAM algorithms in exchange for reduced and simpler CPU demands. CPU speed, amount and speed of storage (RAM and disk), and cost are the three parameters that always bound software performance. To some degree it is almost always possible to trade off between these three resources. Often our algorithm design was guided by the hardware available. The goal of good high performance software design is to avoid underutilization. We consider our hardware budget well utilized when we hit CPU, RAM, and disk storage bottlenecks roughly equally during the build process and we have no cheap upgrade options remaining.

Text S3.3 Initial estimate

Considering that the estimation of our MRIO (and in fact most IO tables) from external constraints is an underdetermined problem, it is worth constructing an initial estimate that is as realistic as possible. For the 187 countries in our MRIO, data availability is vastly different, so that if not carefully planned, setting up an initial estimate can be hampered by case-dependent manual operations. In order to avoid time-consuming labour, we aim at setting up an initial estimate in a way that uses a) the same data source for all countries, b) as much specific data and as little proxy data as possible. We use: First, the National Accounts Main Aggregates Database (MA (United Nations Statistics Division, 2011a)), containing final demand ($y_{\cdot l}^{\cdot s(\mathrm{pu})}$; 4 categories *l*) in purchasers' prices, and value added ($v_{\cdot j}^{ss(\mathrm{ba})}$; 7 sectors *j*) in basic prices, imports ($m_{\cdot\cdot}^{\circ s(\mathrm{fb})}$) and exports ($e_{\cdot\cdot}^{r\circ(\mathrm{fb})}$) valued f.o.b.; second, the UN National Accounts Official Data (OC (United Nations Statistics Division, 2011b)) containing data on gross output $x_{\cdot\cdot}^{ss(\mathrm{ba})}$ and intermediate demand $T_{\cdot\cdot}^{ss(\mathrm{ba})}$, and additional detail for final demand ($y_{\cdot l}^{\cdot s(\mathrm{pu})}$; 6 categories *l*) in purchasers' prices, and value added ($v_{\cdot j}^{ss(\mathrm{ba})}$; 18 sectors *j*) in basic prices; and third the UN ComTrade international trade data (CT (United Nations, 2011)) containing exports $e_{i\cdot}^{rs(\mathrm{fb})}$ valued f.o.b. and imports $m_{i\cdot}^{rs(\mathrm{cf})}$ valued c.i.f. (Table S1).

Table S3.1: Summary of data for each data sources

Data sources	**Abbreviation of data sources**	**Data**	**Formula of data**	**Number of categories**	**Price**
National Accounts Main Aggregates Database	MA	final demand	$y_{\cdot l}^{\cdot s(\mathrm{pu})}$	4	purchasers' prices
		value added	$v_{\cdot j}^{ss(\mathrm{ba})}$	7	basic prices
		imports	$m_{\cdot\cdot}^{\circ s(\mathrm{fb})}$	1	f.o.b.
		Exports	$e_{\cdot\cdot}^{r\circ(\mathrm{fb})}$	1	f.o.b.
UN National Accounts Official Data	OC	gross output	$x_{\cdot\cdot}^{ss(\mathrm{ba})}$	1	basic prices
		intermediate demand	$T_{\cdot\cdot}^{ss(\mathrm{ba})}$	1	purchasers' prices
		final demand	$y_{\cdot l}^{\cdot s(\mathrm{pu})}$	6	purchasers' prices
		value added	$v_{\cdot j}^{ss(\mathrm{ba})}$	18	basic prices
UN ComTrade	CT	exports	$e_{i\cdot}^{rs(\mathrm{fb})}$	About 5000 (HS 6-digits)	f.o.b.
		Imports	$m_{i\cdot}^{rs(\mathrm{cf})}$	About 5000 (HS 6-digits)	c. i. f.

Text S3.3.1 SUTs and IOTs

We construct the diagonal intra-national transaction blocks of the initial estimate according to

$$T_{ij}^{ss(v)} = \frac{\tilde{T}_{ij}^{ss(v)}}{\tilde{T}_{\cdot\cdot}^{ss(\mathrm{pu})}} \frac{T_{\cdot\cdot}^{ss(\mathrm{pu}),\mathrm{OC}}}{v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}} v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{MA}} =$$

$$\underbrace{\frac{\tilde{T}_{ij}^{ss(v)}}{\tilde{T}_{\cdot\cdot}^{ss(\mathrm{pu})}}}_{\substack{\text{sector structure}\\ \text{and valuation scaling}}} \underbrace{\left(\frac{x_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}}{v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}} - 1\right) v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{MA}}}_{\text{magnitude}} \tag{S3a}$$

$$y_{ik}^{ss(v)} = \underbrace{\frac{\tilde{y}_{ik}^{ss(v)}}{\left|\tilde{y}_{\cdot k}^{ss(\mathrm{pu})}\right|}}_{\substack{\text{supply structure}\\ \text{and valuation scaling}}} \underbrace{\frac{y_{\cdot k}^{ss(\mathrm{pu}),\mathrm{OC}}}{y_{\cdot\cdot}^{ss(\mathrm{pu}),\mathrm{OC}}}}_{\substack{\text{use}\\ \text{structure}}} \underbrace{y_{\cdot\cdot}^{ss(\mathrm{pu}),\mathrm{MA}}}_{\text{magnitude}} \tag{S3b}$$

$$v_{lj}^{ss(\mathrm{ba})} = \underbrace{\frac{\tilde{v}_{lj}^{ss(\mathrm{ba})}}{\left|\tilde{v}_{l\cdot}^{ss(\mathrm{ba})}\right|}}_{\substack{\text{use}\\ \text{structure}}} \underbrace{\frac{v_{l\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}}{v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}}}_{\substack{\text{supply}\\ \text{structure}}} \underbrace{v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{MA}}}_{\text{magnitude}} \tag{S3c}$$

$$V_{ij}^{ss(\mathrm{ba})} = \underbrace{\frac{\tilde{V}_{ij}^{ss(\mathrm{ba})}}{\tilde{V}_{\cdot\cdot}^{ss(\mathrm{ba})}}}_{\substack{\text{matrix}\\ \text{structure}}} \underbrace{\frac{x_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}}{v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{OC}}} v_{\cdot\cdot}^{ss(\mathrm{ba}),\mathrm{MA}}}_{\text{magnitude}}, \tag{S3d}$$

where MA and OC denote the source of the data.[1] Equation S3 shows that the magnitudes of each country's initial estimate $\mathbf{T}$, $\mathbf{V}$ and $\mathbf{v}$ ($\mathbf{y}$) are determined by each country's value of $\mathbf{v}$ ($\mathbf{y}$) in the MA database and the ratios in the OC database. The sectoral structure of the initial estimate is determined by proxies $\tilde{T}_{ij}^{ss(v)}$, $\tilde{V}_{ij}^{ss(v)}$, $\tilde{y}_{ij}^{ss(v)}$, and $\tilde{v}_{ij}^{ss(v)}$ in all valuations.

We use the most detailed and diverse tables – from the USA, Japan and Australia – to construct generic 25-sector "international" SUT proxies, which we use for all "common-classed" countries. We used Japan, Australia and USA for two reasons. The first reason is sector detail; all three countries have input-output tables with more than 344 sectors. We have not used China's input-output table, because this table only has 122 sectors, and the intersection of four national IO tables would have included very few sectors. The second reason is the coverage of commodities. Peters and Hertwich (2006) chose other countries' input-output structure based on similar per capita energy use, CO_2 emissions, and GDP. However, even if country A's per capita GDP is similar to country B's per capita GDP the economic structure of country A and B could be completely different. If country A did not produce the main products of country B, embodied emission could change considerably. Therefore, an important criterion is for the basic table structure to cover a wide variety of industries and commodities. The three countries we chose are suitable in this sense because these cover a wide range of industries and commodities such as agriculture, mining, manufacturing and service. This is supported in a study by Andrew, Peters, and Lennox (2009) who found that in constructing an MRIO, modelling a Rest-of-World (RoW) region on the basis of many countries' input-output tables is preferable to choosing a

[1] Neither the MA nor OC database contain information on Taiwan. $\mathbf{T}$, $\mathbf{y}$, $\mathbf{v}$ and $\mathbf{V}$ for Taiwan were constructed based on national data from (National Statistics, 2009).

"representative" country. Our approach in choosing a generic proxy for (RoW) countries without input-output tables follows the same principle. In the future we aim at adding more countries to the SUT proxies. Finally, other studies used approaches similar to ours. For example, Weber and Matthews (2007) and Ahmad and Wyckoff (2003) assumed that the rest of the world has the same structure and emission intensity as the US economy.

Each valuation (v in the equations) is determined by the ratios of these "common-based" countries. The initial estimates for the "separately-classed" countries, where national input-output tables exist in a classification that is more detailed than our common 25-sector classification, are constructed from the most suitable IIOT, CIOT, or SUT proxies, that is from any available table for that country that is closest in terms of year and valuation. In cases where national information on separately-classed is incomplete (for example for certain valuations) we also use the 3-country proxies.

Text S3.3.2 International trade in goods

The accepted approach to estimating international trade matrices in an MRIO table is via trade coefficients $\tau_{ij}^{rs} = f(i,j,r,s)$ that are a function of the exporting country r, the importing country s, the exporting sector i, and the importing sector j. The absolute value of trade flows can then be written as $\tau_{ij}^{rs}\,Tr$, where Tr is some absolute measure of trade from r or into s. The data available to enumerate this equation are imports matrices $M_{ij}^{\circ s}$ included in the input-output tables of some importing countries s, and trade statistics (exports or imports; $(e \vee m)_i^{rs}$) such as from Eurostat (2009), IDE-JETRO (2005), OECD (2006, 2009), and United Nations (2011).

There are however a few hurdles to overcome. First, neither database gives a complete picture of trade, because in the national imports matrices there is no information on the exporting country, and in the trade databases there is no information on the using sector. Second, imported commodities $\{i\}$ in the trade database are usually classified differently to the imported commodities $\{i^{(s)}\}$ in the national input-output tables of the importing country *s*. A "trade-to-importing country" concordance matrix $C_{i,i^{(s)}}$ is necessary to bridge the two classification systems. Further, the international trade blocks have to adhere to the row classification $\{i^{(r)}\}$ of exporting country *r*'s input-output tables, which again usually does not coincide with the commodity classification $\{i\}$ of the trade database, requiring a second "exporting-country-to-trade" concordance matrix $C_{i^{(r)},i}$. Third, import and export data from various sources are inconsistent (Figs. S3.3a-b). Discrepancies can be due to valuation (usually exports are valued f.o.b., and imports c.i.f.), incompleteness with regard to trade in services, transactions coverage (for example Japan excludes transactions smaller than ¥200,000), exchange rates fluctuations, temporal delay between export and import leading to different recorded years, differences in accounting periods (for example India's accounts April to March), and differences in recorded regions (for example if Japan exports to Hong Kong, the import may be recorded as 'China' not 'Hong Kong'; or, an export to the British Virgin Islands may be recorded as 'Great Britain' or 'Virgin Islands') (JETRO, 2009; Oosterhaven, Stelder, & Inomata, 2008; Parniczky, 1980). As a consequence, national imports matrices are generally preferred for representing absolute trade flow, and trade statistics are only used for allocating across trade partners (Bouwmeester & Oosterhaven, 2009).

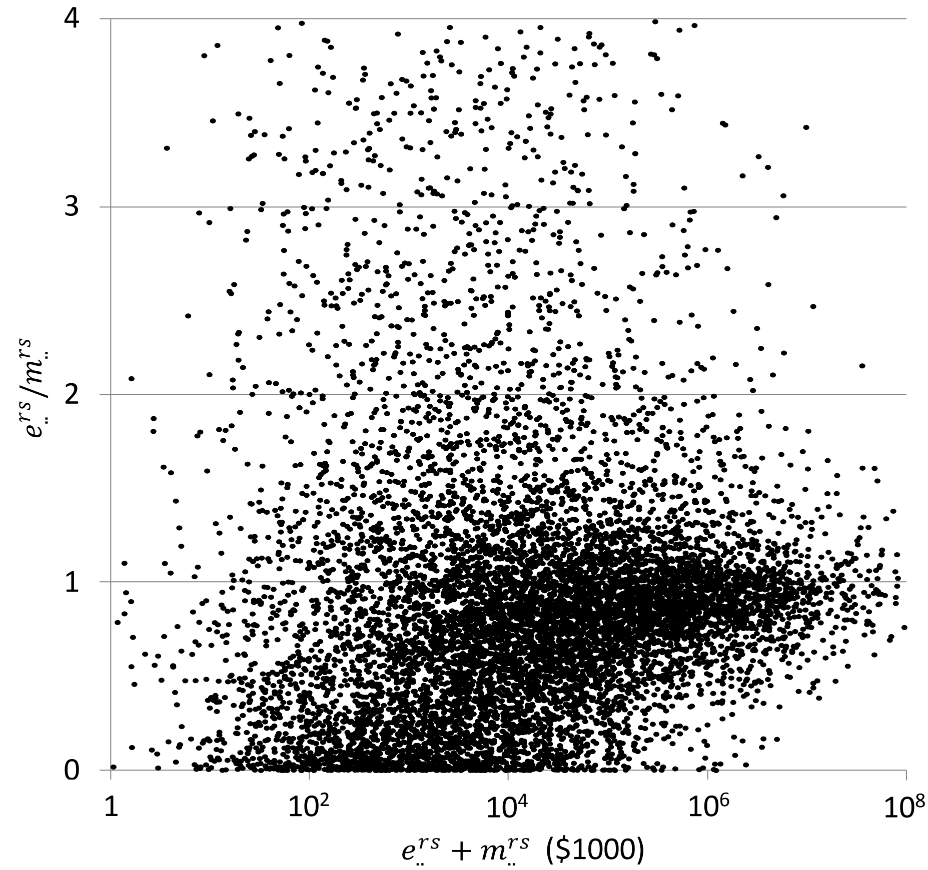
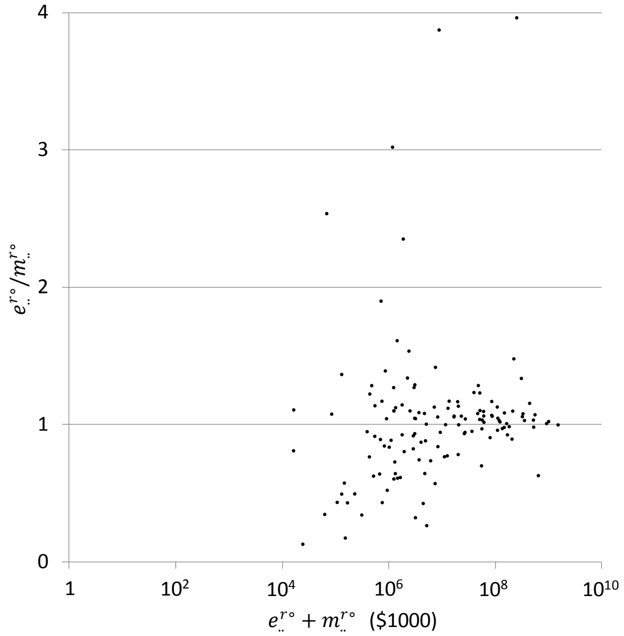


Figure S3.3a: Distribution of export/import ratios $e_{..}^{rs}/m_{..}^{rs}$ across magnitudes of trade flows ($e_{..}^{rs} + m_{..}^{rs}$). As expected, the distribution peaks around $\varrho = 0.9$ (Following Ahmad and Wyckoff's (2003) assumption that 10% of f.o.b. import value reflects insurance and freight costs, or f.o.b. × 0.9 = c.i.f) however inconsistent ratios $\varrho > 1$ and an accumulation of what appears to be severe reporting errors exist for many small transactions.



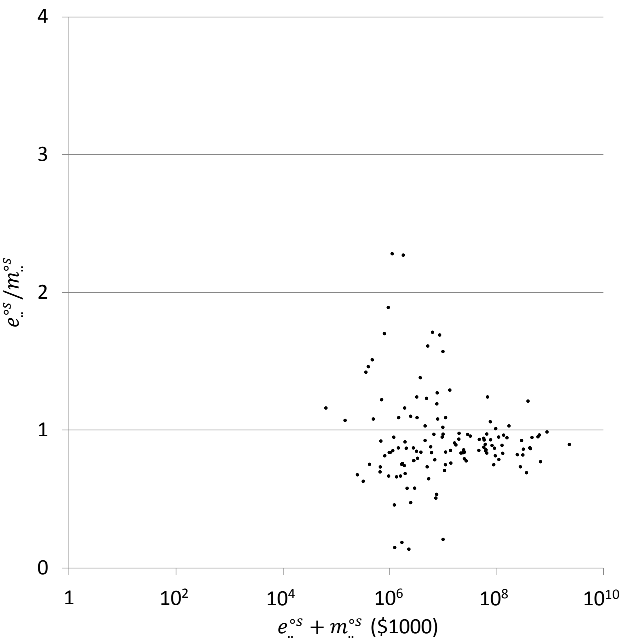


Figure S3.3b: Distribution of export/import ratios $e_{..}^{r\circ}/m_{..}^{r\circ}$ and $e_{..}^{\circ s}/m_{..}^{\circ s}$ across magnitudes of trade flows $(e_{..}^{r\circ} + m_{..}^{r\circ})$ and $(e_{..}^{\circ s} + m_{..}^{\circ s})$. As expected, the distributions peak around $\varrho = 0.9$, however inconsistent ratios $\varrho > 1$ and an accumulation of what appears to be severe reporting errors exist for small transactions even after summing over importing or exporting countries. Plotting $e_{i.}^{..}/m_{i.}^{..}$ by traded commodity against $e_{i.}^{..} + m_{i.}^{..}$ gives even worse results.

These three circumstances necessitate a general formulation $\sum_{i,i^{(s)}} C_{i^{(r)},i} \frac{(e \vee m)^{rs}_{i\cdot}}{(e \vee m)^{\circ s}_{i\cdot}} C_{i,i^{(s)}} M^{\circ s}_{i^{(s)} j^{(s)}}$ for estimating international transaction from incomplete data, with the term $M^{\circ s}_{i^{(s)} j^{(s)}}$ used for modeling the sectoral use structure, and the term $\frac{(e \vee m)^{rs}_{i\cdot}}{(e \vee m)^{\circ s}_{i\cdot}}$ used for modelling the country origin structure of traded commodities. The concordance matrices have to adhere to certain normality conditions; most importantly, the rowsum or column sum should be 1, so that the total value of the aggregated matrix still equals the total value of the original matrix. We construct the off-diagonal international transaction blocks of the initial estimate according to[2]

$$T^{rs(\mathrm{ba})}_{i^{(r)} j^{(s)}} = \underbrace{\frac{\tilde{e}^{r\circ\,(\mathrm{ba})}_{i^{(r)}\cdot}}{\tilde{e}^{r\circ\,(\mathrm{fb})}_{i^{(r)}\cdot}}}_{\text{ba scaling}} \underbrace{\frac{e^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}_{\cdot\cdot}}{m^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}_{\cdot\cdot}}}_{\text{fb scaling}} \sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{M^{\circ s\,(\mathrm{cf})}_{i^{(s)} j^{(s)}}}_{\substack{\text{sector structure}\\ \text{and magnitude}}} \tag{S4a}$$

$$y^{rs(\mathrm{ba})}_{i^{(r)} k^{(s)}} = \underbrace{\frac{\tilde{e}^{r\circ\,(\mathrm{ba})}_{i^{(r)}\cdot}}{\tilde{e}^{r\circ\,(\mathrm{fb})}_{i^{(r)}\cdot}}}_{\text{ba scaling}} \underbrace{\frac{e^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}_{\cdot\cdot}}{m^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}_{\cdot\cdot}}}_{\text{fb scaling}} \sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{N^{\circ s\,(cf)}_{i^{(s)} k^{(s)}}}_{\substack{\text{sector structure}\\ \text{and magnitude}}} \tag{S4b}$$

$$T^{rs(\mathrm{m}n=1:2)}_{i^{(r)} j^{(s)}} = \underbrace{\frac{1}{2}\left[\frac{v^{rr(\mathrm{ba}),\mathrm{MA}}_{\cdot n}}{v^{rr(\mathrm{ba}),\mathrm{MA}}_{\cdot n=\mathrm{trd,tra}}} + \frac{v^{ss(\mathrm{ba}),\mathrm{MA}}_{\cdot n}}{v^{ss(\mathrm{ba}),\mathrm{MA}}_{\cdot n=\mathrm{trd,tra}}}\right]}_{\substack{\text{margin type}\\ \text{structure}}} \underbrace{\left(1 - \frac{\tilde{e}^{r\circ\,(\mathrm{ba})}_{i^{(r)}\cdot}}{\tilde{e}^{r\circ\,(\mathrm{fb})}_{i^{(r)}\cdot}}\right)}_{\text{margin scaling}} \underbrace{\frac{e^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}_{\cdot\cdot}}{m^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}_{\cdot\cdot}}}_{\text{fb scaling}}$$

$$\sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{M^{\circ s\,(\mathrm{cf})}_{i^{(s)} j^{(s)}}}_{\substack{\text{sector structure}\\ \text{and magnitude}}} \tag{S4c}$$

[2] The CT database does not contain information on Taiwan. **T**, **y** and **v** for Taiwan were constructed using trade data from (SourceOECD, 2009).

$$y_{i^{(r)}k^{(s)}}^{rs(\mathrm{mn}=1:2)} = \underbrace{\frac{1}{2}\left[\frac{v_{\cdot n}^{rr(\mathrm{ba}),\mathrm{MA}}}{v_{\cdot n=\mathrm{trd,tra}}^{rr(\mathrm{ba}),\mathrm{MA}}} + \frac{v_{\cdot n}^{ss(\mathrm{ba}),\mathrm{MA}}}{v_{\cdot n=\mathrm{trd,tra}}^{ss(\mathrm{ba}),\mathrm{MA}}}\right]}_{\text{margin type structure}} \underbrace{\left(1 - \frac{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(\mathrm{ba})}}{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(\mathrm{fb})}}\right)}_{\text{margin scaling}} \underbrace{\frac{e_{\cdot\cdot}^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}}{m_{\cdot\cdot}^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}}}_{\text{fb scaling}}$$

$$\sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{N_{i^{(s)}k^{(s)}}^{\circ s\,(cf)}}_{\text{sector structure and magnitude}} \tag{S4d}$$

$$T_{i^{(r)}j^{(s)}}^{rs(\mathrm{tx})} = \overbrace{\sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{\frac{\widetilde{M}_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{tx})}}{\widetilde{M}_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})}}}_{\text{tx scaling}} \underbrace{M_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})}}_{\text{sector structure and magnitude}}}^{\text{taxes on imports}}$$

$$+ \overbrace{\underbrace{\frac{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(tx)}}{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(fb)}}}_{\text{tx scaling}} \underbrace{mos_{r,s,i^{(r)},i,i^{(s)}}}_{\text{magnitude, country and supply structure}} \underbrace{\frac{M_{i^{(s)}j^{(s)}}^{\circ s\,(cf)}}{M_{i^{(s)}\cdot}^{\circ s\,(cf)}}}_{\text{use structure}}}^{\text{taxes on exports}} \tag{S4e}$$

$$y_{i^{(r)}k^{(s)}}^{rs(\mathrm{tx})} = \overbrace{\sum\nolimits_{i,i^{(s)}} \underbrace{os_{r,s,i^{(r)},i,i^{(s)}}}_{\text{origin structure}} \underbrace{\frac{\widetilde{N}_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{tx})}}{\widetilde{N}_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})}}}_{\text{tx scaling}} \underbrace{N_{i^{(s)}k^{(s)}}^{\circ s\,(\mathrm{cf})}}_{\text{sector structure and magnitude}}}^{\text{taxes on imports}}$$

$$+ \overbrace{\underbrace{\frac{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(tx)}}{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(fb)}}}_{\text{tx scaling}} \underbrace{mos_{r,s,i^{(r)},i,i^{(s)}}}_{\text{magnitude, country and supply structure}} \underbrace{\frac{N_{i^{(s)}k^{(s)}}^{\circ s\,(cf)}}{N_{i^{(s)}\cdot}^{\circ s\,(cf)}}}_{\text{use structure}}}^{\text{taxes on exports}} \tag{S4f}$$

$$T_{i^{(r)}j^{(s)}}^{rs(\mathrm{sb})} = \overbrace{\underbrace{\frac{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(sb)}}{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(fb)}}}_{\text{sb scaling}} \underbrace{mos_{r,s,i^{(r)},i,i^{(s)}}}_{\text{magnitude, country and supply structure}} \underbrace{\frac{M_{i^{(s)}j^{(s)}}^{\circ s\,(cf)}}{M_{i^{(s)}\cdot}^{\circ s\,(cf)}}}_{\text{use structure}}}^{\text{subsidies on exports}} \tag{S4g}$$

$$y_{i^{(r)}k^{(s)}}^{rs(\mathrm{sb})} = \overbrace{\underbrace{\frac{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(sb)}}{\tilde{e}_{i^{(r)}\cdot}^{r\circ\,(fb)}}}_{\text{sb scaling}} \underbrace{mos_{r,s,i^{(r)},i,i^{(s)}}}_{\text{magnitude, country and supply structure}} \underbrace{\frac{N_{i^{(s)}k^{(s)}}^{\circ s\,(cf)}}{N_{i^{(s)}\cdot}^{\circ s\,(cf)}}}_{\text{use structure}}}^{\text{subsidies on exports}} \tag{S4h}$$

where

$$os_{r,s,i^{(r)},i,i^{(s)}} = C_{i^{(r)},i} \frac{m_{i\cdot}^{rs(\mathrm{cf}),\mathrm{CT}} + \left\{m_{\cdot\cdot}^{rs(\mathrm{cf}),\mathrm{CT}} = 0\right\} e_{i\cdot}^{rs(\mathrm{fb}),\mathrm{CT}} \frac{m_{\cdot\cdot}^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}}{e_{\cdot\cdot}^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}}}{m_{i\cdot}^{\circ s(\mathrm{cf}),\mathrm{CT}} + \sum_{\left\{r \middle| m_{\cdot\cdot}^{rs(\mathrm{cf}),\mathrm{CT}} = 0\right\}} e_{i\cdot}^{r\,s(\mathrm{fb}),\mathrm{CT}} \frac{m_{\cdot\cdot}^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}}{e_{\cdot\cdot}^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}}} C_{i,i^{(s)}}$$

$$mos_{r,s,i^{(r)},i,i^{(s)}} = C_{i^{(r)},i}\left(e_{i\cdot}^{rs\,(fb),CT} + \{e_{\cdot\cdot}^{rs\,(fb),CT} = 0\}m_{i\cdot}^{rs\,(cf),CT}\,\frac{e_{\cdot\cdot}^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}}{m_{\cdot\cdot}^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}}\right)C_{i,i^{(s)}}$$

are the two structure terms used in the set of Equations S4. In the equation for margins n=1:2, we use the trade (trd) and transport (tra) sectors in the UN SNA Main Aggregates database to distribute across margin types. We use $\frac{1}{2}\left[\frac{v_{\cdot n}^{rr(\mathrm{ba}),\mathrm{MA}}}{v_{\cdot n=\mathrm{trd,tra}}^{rr(\mathrm{ba}),\mathrm{MA}}} + \frac{v_{\cdot n}^{ss(\mathrm{ba}),\mathrm{MA}}}{v_{\cdot n=\mathrm{trd,tra}}^{ss(\mathrm{ba}),\mathrm{MA}}}\right]$, because we assume that international margins are equally likely to be supplied by the supplying or receiving country. We use a total aggregate of the cif-to-fob scaler $\frac{e_{\cdot\cdot}^{\circ\cdot(\mathrm{fb}),\mathrm{CT}}}{m_{\cdot\cdot}^{\circ\cdot(\mathrm{cf}),\mathrm{CT}}}$ throughout because disaggregated ratios proved to fluctuate excessively (see Figs. S3.4a-b). Where national imports matrices $M_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})}$ and $N_{i^{(s)}k^{(s)}}^{\circ s\,(\mathrm{cf})}$ are not available, we approximate

$$M_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})} = \underbrace{\frac{\widetilde{M}_{i^{(s)}j^{(s)}}^{\circ s\,(\mathrm{cf})}}{\widetilde{M}_{\cdot\cdot}^{\circ s\,(\mathrm{cf})} + \widetilde{N}_{\cdot\cdot}^{\circ s\,(\mathrm{cf})}}}_{\text{matrix structure}}\;\underbrace{m_{\cdot\cdot}^{\circ s(\mathrm{cf}),\mathrm{MA}}}_{\text{magnitude}}$$

and

$$N_{i^{(s)}k^{(s)}}^{\circ s\,(\mathrm{cf})} = \underbrace{\frac{\widetilde{N}_{i^{(s)}k^{(s)}}^{\circ s\,(\mathrm{cf})}}{\widetilde{M}_{\cdot\cdot}^{\circ s\,(\mathrm{cf})} + \widetilde{N}_{\cdot\cdot}^{\circ s\,(\mathrm{cf})}}}_{\text{matrix structure}}\;\underbrace{m_{\cdot\cdot}^{\circ s(\mathrm{cf}),\mathrm{MA}}}_{\text{magnitude}}. \tag{S5}$$

The equations in this section show that national imports matrices are key data items for estimating country-pair-specific trade matrices by pro-rating across countries of origin and using sectors.

Eq. S4a basically means that we estimate the international trade block in basic (factory or farm gate) prices by disaggregating the import matrix (M) using bilateral trade data for describing the imports origin structure (os) for each importing country. Two obstacles in this estimation are that a) the raw import matrix is expressed in c.i.f. (cost-insurance-freight) prices, and that b) the exporting country's classification is not same as the importing country's classification. Therefore, we first convert c.i.f. prices to f.o.b. (free-on-board) prices using COMTRADE data for deriving c.i.f.-to-f.o.b. scalers, and then convert f.o.b. prices to basic prices using national IO table for deriving f.o.b.-to-basic-price scalers. We change the import matrix's origin structure to match the exporting country's classification using concordance matrix and COMTRADE's bilateral trade data. Some countries do not report their exports and imports to COMTRADE. In this case, we have used other country's reports to approximate the origin structure. For example, if Iran doesn't provide data for imports from Japan then we used exports from Japan to Iran that Japan reports to COMTRADE.

Text S3.3.3 International trade in services

The ComTrade database (United Nations, 2011) does not include trade in services. We added service sectors at the end of all concordance, and use

$$os_{r,s,i^{(r)},i,i^{(s)}} = \frac{m_{..}^{rs(\mathrm{cf}),\mathrm{CT}} + \left\{m_{..}^{rs(\mathrm{cf}),\mathrm{CT}} = 0\right\} e_{..}^{rs(\mathrm{fb}),\mathrm{CT}}}{m_{..}^{\circ s(\mathrm{cf}),\mathrm{CT}} + \sum_{\left\{r \middle| m_{..}^{rs(\mathrm{cf}),\mathrm{CT}} = 0\right\}} e_{..}^{rs(\mathrm{fb}),\mathrm{CT}}} \tag{S6}$$

$$mos_{r,s,i^{(r)},i,i^{(s)}} =$$

$$\left(e_{..}^{ro\,(fb),MA} - e_{..}^{r^{\circ}\,(fb),CT}\right) \frac{e_{..}^{rs\,(fb),CT} + \left\{e_{..}^{rs\,(fb),CT} = 0\right\} m_{..}^{rs\,(cf),CT} \frac{e_{..}^{\circ\cdot(fb),CT}}{m_{..}^{\circ\cdot(cf),CT}}}{e_{..}^{r^{\circ}\,(fb),CT} + \sum_{\left\{s \middle| e_{..}^{rs\,(fb),CT} = 0\right\}} m_{..}^{rs\,(cf),CT} \frac{e_{..}^{\circ\cdot(fb),CT}}{m_{..}^{\circ\cdot(cf),CT}}} \tag{S7}$$

as the origin structure term. As an initial estimate of the service trade we used commodity import and export ratios. The ensuing relationships are analogous to Equations S4a–f.

Text S3.3.4 Re-exports

According to the United Nations (United Nations, 2009a), "*exports of a country can be distinguished as exports of domestic goods and exports of foreign* *goods. The second class is generally referred to as re-exports*". Similarly, "*imports can be distinguished as imports of foreign goods and imports of domestic goods. Import of domestic goods is referred as re-imports*". Re-exports and re-imports can cause some of the inconsistencies of trade data, so that their explicit inclusion into the MRIO leads to less data conflict. Therefore we added only one column (row) of re-exports (re-imports) into our MRIO. We construct re-export initial estimates (rows) according to

$$T^{rs(v)}_{I^{(r)}+1j^{(s)}} = RX^{(r)} \underbrace{\frac{T^{rs(v)}_{\cdot j^{(s)}}}{T^{r\circ(v)}_{\cdot\cdot}+y^{r\circ(v)}_{\cdot\cdot}}}_{\text{use and destination structure}}, \quad y^{rs(v)}_{I^{(r)}+1k^{(s)}} = RX^{(r)} \underbrace{\frac{y^{rs(v)}_{\cdot k^{(s)}}}{T^{r\circ(v)}_{\cdot\cdot}+y^{r\circ(v)}_{\cdot\cdot}}}_{\text{use and destination structure}} \tag{S8}$$

where $I^{(r)}$ is the total number of sectors in country *r*'s classification, and $RX^{(r)}$ are total re-exports of country *r*. Re-import initial estimates (columns, into intermediate demand only) can be expressed as

$$T^{rs(v)}_{i^{(r)}J^{(s)}+1} = RX^{(r)} \underbrace{\frac{T^{rs(v)}_{i^{(r)}\cdot}}{T^{\circ s(v)}_{\cdot\cdot}}}_{\text{origin and supply structure}}, \tag{S9}$$

where $J^{(s)}$ is the total number of sectors in country *s*'s classification. Finally, the row and column sum balance reads

$$T^{r\circ(v)}_{I^{(r)}+1\cdot} + y^{r\circ(v)}_{I^{(r)}+1\cdot} = RX^{(r)} = T^{\circ s(v)}_{\cdot J^{(s)}+1}. \tag{S10}$$

Text S3.3.5 FISIM

Some financial intermediaries defray cost and generate profits through imposing borrowing and lending rate differentials on the capital they service, thus avoiding direct transactions with customers. In such cases financial intermediation services are indirectly measured (FISIM). Whilst the SNA 1968 stipulates to record such estimated output as the intermediate consumption of a nominal industry, the SNA 1993 allows allocating FISIM across using sectors (Commission of the European Communities et al., 1993). Reporting practices differ amongst countries: the UK's accounts always include a nominal FISIM sector, Japan's accounts have FISIM always allocated across users, and Spain switched from nominal FISIM sector to user allocation between 1999 and 2000. On one hand there is no information to transform one practice into the other. On the other hand FISIM are not negligible, hence they must be included to avoid severe account imbalances. We have hence decided to always include a nominal FISIM sector into our MRIO classification, and to leave this sector empty where FISIM is allocated across users. Note that in cases such as Spain, this can lead to sharp discontinuities over time when practices are changed. In order to eliminate such discontinuities we follow a procedure suggested by EUROSTAT, which is to spread total FISIM to using industries proportionally to their share of gross output, and reduce the operational surplus of each industry by the pro-rated amount.

Text S3.4 Concordances and maps

In order to carry out calculations on trade blocks most effectively, we link national product classifications (NPC; N_C classes for country C) to the 6-digit subheadings of the OECD Harmonised System (HS6; N_{HS6} classes), and store those as N_C x N_{HS6} sparse binary matrices. The link is established directly for countries where a NPC-HS6 concordance is provided. Alternatively, we have produced NPC-HS6 concordances in a two-step process via either NPC↔ISIC (International Standard Industrial Classification of All Economic Activities) and ISIC↔HS6 or NPC↔CPC (Central Product Classification) and CPC↔HS6. In case of trade in services, we use the CPC service classification instead of the

Harmonised System.

Binary concordance matrices **C** cannot be used to convert vectors **v** from one to another classification (via matrix multiplication $\mathbf{v}' = \mathbf{C}\mathbf{v}$), because multiple correspondences of an aggregate product in the disaggregated classification mean that **C** is not normalised, so that **v**' would have a row sum different to that of **v**. In order to enumerate the trade blocks of our MRIO (Equations S4a-f), we require both row- and column-normalised mapping matrices, or maps. We calculate these maps from concordances by pro-rating with a suitable proxy trade variable (see Text S3.4.2). In most cases, HS6 is always more detailed than national input-output classification, so that the correspondence is unique, and the binary concordance matrix is already normalised to distribute HS6-classed data across national classes, and only needs to be normalised to distribute national-classed data across HS6. This is achieved by using HS6 import data as a proxy. In a few cases (notably Japan and the USA), parts of the national input-output classifications are more detailed than HS6, thus requiring a second normalisation to distribute HS6-classed data across national classes.

Problems with concordances appear especially when sector classifications aggregate sectors that are substantially different in nature. For example, some databases do not separate electricity generation from electricity distribution, presumably because these services are offered by the same utility company. In these cases, one cannot even clearly delineate pure goods from pure services, let alone uniquely concord such a classification to ISIC or HS, since electricity is generally included in the category "goods" whilst its distribution is classed a "service". The only remaining solution is to aggregate electricity distribution into electricity generation. For example, the UN National Accounts Official Country database provides the totals for both goods and services exported and imported, and the Eora tables use these data as four constraints per country. If one country features an aggregate electricity generation/distribution sector, we would strictly speaking need to aggregate these four constraints into two total export and import constraints. To avoid such a loss of detail, we regard electricity distribution as a good, like electricity, enabling us to keep goods and services export and import data as separate constraints.

Text S3.4.1 Normalisation of concordance matrices used for trade flow estimation

The form in Equations S4 and S5 must adhere to the normalisation

$$\sum_{r,i^{(r)},j^{(s)}} MRIO^{rs}_{i^{(r)}j^{(s)}} = \sum_{i^{(s)},j} M^{s}_{i^{(s)}j^{(s)}} = M^{s}, \tag{S11}$$

or

$$\begin{aligned} &\sum_{r,i^{(r)},j^{(s)}} \sum_{i,i^{(s)}} C_{i^{(r)},i}\, t_i^{rs}\, C_{i,i^{(s)}}\, M^{s}_{i^{(s)}j^{(s)}} = M^{s} \\ \Leftrightarrow &\sum_{r,i^{(r)},i} C_{i^{(r)},i}\, t_i^{rs} \sum_{i^{(s)},j^{(s)}} C_{i,i^{(s)}}\, M^{s}_{i^{(s)}j^{(s)}} = M^{s}. \end{aligned} \tag{S12}$$

The equality in Equation S11 can be fulfilled if

$$\Leftarrow \sum_{i^{(s)},j^{(s)}} C_{i,i^{(s)}} M^{s}_{i^{(s)}j^{(s)}} = M_i^{s} \ \wedge\ \sum_i M_i^{s} = M^{s} \wedge \sum_{r,i^{(r)}} C_{i^{(r)},i}\, t_i^{rs} = 1\ \forall\, i\,. \tag{S13}$$

This is because

$$\begin{aligned} &\sum_{r,i^{(r)},i} C_{i^{(r)},i} t_i^{rs} \sum_{i^{(s)},j^{(s)}} C_{i,i^{(s)}} M^{s}_{i^{(s)}j^{(s)}} \\ &= \sum_{r,i^{(r)},i} C_{i^{(r)},i}\, t_i^{rs} M_i^{s} \\ &= \sum_i M_i^{s} \sum_{r,i^{(r)}} C_{i^{(r)},i}\, t_i^{rs} \\ &= \sum_i M_i^{s} 1_i = \sum_i M_i^{s} = M^{s}. \end{aligned} \tag{S14}$$

Here, the M_i^{s} are the row sums of $M^{s}_{i^{(s)}j^{(s)}}$ re-classified from row classification $\{i^{(s)}\}$ into trade database classification $\{i\}$. The three conditions in Equation S14 have the form of weighted sums over $i^{(s)}$ and $i^{(r)}$. Summing the first conditions over i yields

$$\sum_{i^{(s)}} \sum_i C_{i,i^{(s)}} M^{s}_{i^{(s)}} = \sum_{i^{(s)}} M^{s}_{i^{(s)}} \sum_i C_{i,i^{(s)}} = M^{s}\,, \tag{S15}$$

from which we can deduce the normalisation condition on $C_{i,i^{(s)}}$ as

$$\sum_i C_{i,i^{(s)}} = 1 \,\forall\, i^{(s)}. \tag{S16}$$

Expressed in words, this condition says that each commodity $i^{(s)}$ in the national input-output tables of importing country *s* must be fully and uniquely allocated to one or more trade classes i. Summing the second condition over i yields

$$\sum_{r,i^{(r)}} C_{i^{(r)},i} t_i^{rs} = \sum_r \frac{T_i^{rs}}{\sum_r T_i^{rs}} \sum_{i^{(r)}} C_{i^{(r)},i} = 1 \,\forall\, i, \tag{S17}$$

from which we can deduce the normalisation condition on $C_{i^{(r)},i}$ as

$$\sum_{i^{(r)}} C_{i^{(r)},i} = 1 \,\forall\, i\,. \tag{S18}$$

Expressed in words, this condition says that each trade class i in the trade database must be fully and uniquely allocated to one or more commodities $i^{(r)}$ in the national input-output tables of exporting country *r*.

Both concordance matrices hence have to be normalised so that their column sums equal 1. This is a direct consequence of the choice of the national imports matrix $M^s_{i^{(s)}j^{(s)}}$ as a scaler, since this imports matrix is located at the right hand side of the product in Equation S12, and its summed value has to be preserved.

Text S3.4.2 Creation of maps from concordances

Let $\mathbf{C}$ be a $n \times m$ binary concordance matrix. Let $m > n$, so that the columns of $\mathbf{C}$ contain the disaggregated classification. Then, there will be rows i of $\mathbf{C}$ with $\sum_j C_{ij} > 1$. During the normalisation of $\mathbf{C}$ to a map, these rows have to be scaled so that $\sum_j C_{ij} = 1$. Let $\mathbf{x}_m$ be a row vector containing the m-classed proxy variable to be used for pro-rating, and $\hat{\mathbf{x}}_m$ be the diagonal matrix corresponding to $\mathbf{x}_m$. Using an m-classed summation vector $\mathbf{1}_m$, the n-classed representation of $\mathbf{x}_m$

can be written as $\mathbf{x}_n = \mathbf{C}\hat{\mathbf{x}}_m \mathbf{1}_m$. The row-normalised map (row map) corresponding to $\mathbf{C}$ is then $\mathbf{M} = \left(\widehat{\mathbf{C}\hat{\mathbf{x}}_m \mathbf{1}_m}\right)^{-1} \mathbf{C}\hat{\mathbf{x}}_m = \hat{\mathbf{x}}_n^{-1} \mathbf{C}\hat{\mathbf{x}}_m$. Column-normalisation proceeds similarly.

Text S3.5 A small example

Here we provide a simplified small example showing how we treat conflicting data, time series data, different sector detail, and so on. Further detail is provided in this paper and also in Geschke et al. (2011).

Assume we have data for a 3-sector IO table in 2000 (Table S3.5.1), a 2-sector intermediate demand matrix in 2001 (Table S3.5.2), and a 1-sector final demand and value added scalar in 2000 and 2001 (Table S3.5.3).

Table S3.5.1: 2000 input-output table

	Primary industry	Secondary industry	Services	Final demand
Primary industry	10	1	3	10
Secondary industry	3	20	4	15
Services	1	5	10	20
Value added	10	16	19	

Table S3.5.2: 2001 input-output table

	Goods	Services
Goods	40	9
Services	7	11

Table S3.5.3: Final demand and value added in 2000 and 2001

Total final demand in 2000	50

Total value added in 2000	50
Total final demand in 2001	60
Total value added in 2001	60

We use the 3-sector IO table in 2000 for the year 2000 initial estimate. Then we write the data in Tables S3.5.2 and S3.5.3 as additional constraints. The optimizer handles the MRIO table as a vector (*SI Appendix*, Text S3.2, above) so we vectorize the initial estimate **a** as

$$\mathbf{a} = \begin{pmatrix} 10 \\ 3 \\ 1 \\ \vdots \\ 10 \\ 15 \\ 20 \end{pmatrix}. \tag{S19}$$

In 2000, we have constraints for total final demand and value added,

$$\mathbf{c} = \begin{pmatrix} 50 \\ 50 \end{pmatrix}. \tag{S20}$$

Total final demand corresponds to "1" values (in grey) in Table S3.5.4,

Table S3.5.4: Final demand correspondence

	Primary industry	Secondary industry	Services	Final demand
Primary industry	0	0	0	1
Secondary industry	0	0	0	1
Services	0	0	0	1
Value added	0	0	0	

and the total value added corresponds to the "1" values (grey) in Table S5.5,

Table S3.5.5: Value added correspondence

	Primary industry	Secondary industry	Services	Final demand
Primary industry	0	0	0	0
Secondary industry	0	0	0	0
Services	0	0	0	0
Value added	1	1	1	

So we can vectorize and transpose these two binary correspondence matrices to create the constraint equation rows in **G** for the two constraints established at step (S20):

$$\mathbf{G} = \begin{pmatrix} 0 & 0 & 0 & 0 & \dots & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & \dots & 1 & 0 & 0 & 0 \end{pmatrix} \tag{S21}$$

Following the optimization problem formulated in Text S3.2 and Eqs S19-21 we establish the following problem to find a solution **p** (where **p** is the MRIO table **a** extended with slack variables **e** to allow deviation from prescribed constraint values **c**, as described in Text S3.2) that fulfils all constraints,

$$\min_{\mathbf{p}} f(\mathbf{p}, \mathbf{p}_0) \quad \text{subject to} \quad \mathbf{Gp} = \mathbf{c} \tag{S22}$$

Of course, our study considers other problems such as upper and lower bounds and data uncertainty, but for simplicity we will not cover these situations in this example. In 2001, we use the 2000 MRIO solution as an initial estimate for the 2001 MRIO.

The aggregated 2-sector intermediate demand matrix for 2001 is handled in the same way. The constraints for the 2001 MRIO would include

$$\mathbf{c} = \begin{pmatrix} 40 \\ 7 \\ 9 \\ 11 \\ 60 \\ 60 \end{pmatrix} \tag{S23}$$

$$\mathbf{G} = \begin{pmatrix} 1 & 1 & 0 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & \dots & 1 & 0 & 0 & 0 \end{pmatrix} \tag{S24}$$

For example, the first element of the intermediate demand matrix in 2001 (40 in Table S3.5.2) corresponds to four data points in the initial estimate MRIO as seen in Table S3.5.6:

Table S3.5.6: Intermediate demand correspondence example

	Primary industry	Secondary industry	Services	Final demand
Primary industry	1	1	0	0
Secondary industry	1	1	0	0
Services	0	0	0	0
Value added	0	0	0	

Using the 2000 solution as an initial estimate and the 2001 constraints we can solve the optimization problem and arrive at a 2001 MRIO solution. Using this approach we can treat any data as constraints in an input-output table with any level of sector detail.

This example shows only one sheet (basic prices) for simplicity, but our study has 5 price sheets (basic price, taxes on products, subsidies on products, trade margin, and transport margin) as illustrated in Figure S3.5a.

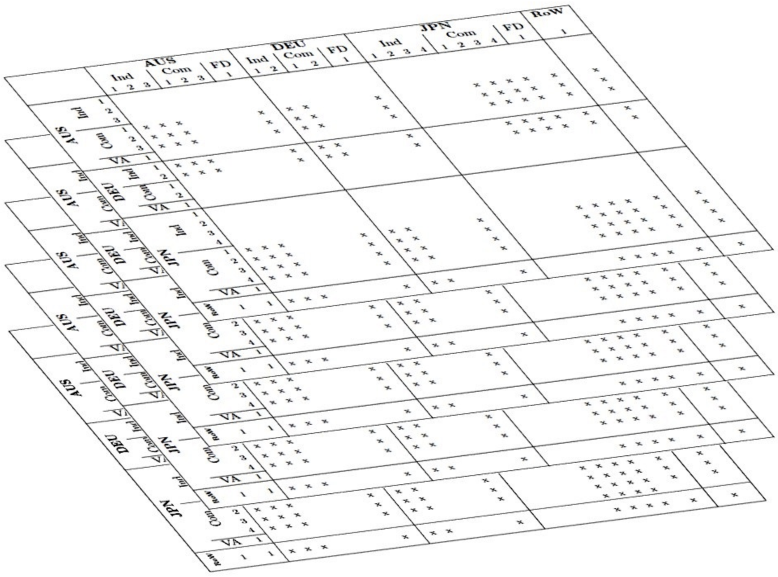


Figure S3.5a: Stack of input-output tables representing basic prices, margins and taxes.

Text S3.6 Data Sources

Text S3.6.1 MRIO data sources

The Eora tables incorporate a multitude of raw data from national and international organisations. The main sources for the monetary MRIO table are

1. Input-output tables and main aggregates data for 74 countries sourced from national statistical offices (*SI Appendix*, Table S3.3 and Text S3.6)
2. Input-output compendia (Eurostat, 2009; IDE-JETRO, 2005; OECD, 2006, 2009), about 42,000,000 raw data points (Eurostat covers 29 countries and 60 sectors input-output tables from 1995-2007; IDE-JETRO provides 10 national IO tables with 76 sectors in 2000; OECD provides 48 national IO tables with 48 sectors from the 1990s to 2005)
3. the UN National Accounts Main Aggregates Database (United Nations Statistics Division, 2011a), about 120,000 raw data points

4. the UN National Accounts Official Data (United Nations Statistics Division, 2011b), about 1,600,000 raw data points,
5. the UN ComTrade international trade database (United Nations, 2011), about 25,000,000 raw data points (covering 209 countries), and
6. the UN ServiceTrade international trade database (United Nations, 2009b), about 480,000 raw data points (covering 194 countries).

Text S3.6.2 Satellite account data sources

The satellite accounts are constructed using the following data sources:

1. Energy use, greenhouse gas emissions and emissions to air: numerous national databases, for example (Nansai, Moriguchi, & Tohno, 2010); international databases, for example from the International Energy Agency, the OECD, the UN Statistical Division, the US Energy Information Agency, and the EDGAR database (European Commission Joint Research Centre & Agency, 2012);
2. Human Appropriation of Net Primary Production (HANPP) from (Imhoff et al., 2004);
3. Ecological Footprint from the National footprint and Biocapacity Accounts (Global Footprint Network, 2010);
4. Water requirement from the WaterStat database (Chapagain & Hoekstra, 2004);
5. Threatened species from the IUCN Red List (IUCN, 2011).

Indicators 1 and 3 are available annually. The other indicators are available for a single year, though users may choose to use those indicators with an MRIO for a different year. Using an indicator with a different-year MRIO is strictly speaking invalid however it could be useful in a situation where the indicator is slow-changing, such as HANPP, but where using a contemporary

MRIO with recent trade patterns is more important.

We use the optimizer to combine/resolve multiple sources of satellite indicator data. For energy, we preferred national energy data (such as 3EID for Japan) because these data are constructed for input-output tables as an initial estimate. If national data are not available, then we used IEA extended energy balances, or U.S. Energy Information Administration (EIA) data as an initial estimate. We then used *all* available energy data as constraints and ran the optimization algorithm. For greenhouse gas emissions, we have used EDGAR data as an initial estimate because EDGAR follows IPCC classification and covers detailed sectors. For indicators where we only have one data source (e.g. Ecological Footprint and HANPP) the optimizer has no effect as there is no conflict to resolve.

Text S3.6.3 Detailed list of national input-output tables data sources

We have used following national input-output tables. We showed only primary data sources for each country to avoid duplication. In addition to these tables, we have used Eurostat (2009), IDE-JETRO (2005), OECD (2006, 2009) database.

Aruba

Central Bureau of Statistics Aruba. (2002). Supply and use table 1995-2000. *National Accounts of Aruba, 1995-2000.* Retrieved November 16, 2010, from http://www.cbs.aw/cbs/manageDocument.do?dispatch=view&id=488

Central Bureau of Statistics Aruba. (2002). Supply and use table 1995-1998. *National Accounts of Aruba, 1995-1998.* Retrieved November 16, 2010, from http://www.cbs.aw/cbs/manageDocument.do?dispatch=view&id=487

Central Bureau of Statistics Aruba. (2003). Supply and use table 1999-2002. *National Accounts of Aruba, 1999-2002.* Retrieved November 16, 2010, from http://www.cbs.aw/cbs/manageDocument.do?dispatch=view&id=489

Central Bureau of Statistics Aruba. (2007). Supply and use table 2000. *National Accounts of Aruba, 2000 - 2006.* Retrieved November 16, 2010, from http://www.cbs.aw/cbs/manageDocument.do?dispatch=view&id=1220

Netherlands Antilles

Central Bureau Of Statistics Netherlands Antilles. (2009). The Supply and Use Table 2004 Netherlands Antilles. Retrieved November 16, 2010, from http://www.cbs.an/files/SUS NA 2004.pdf

Argentina

Instituto Nacional de Estadística y Censos. (2001). Matriz de Insumo - Producto Argentina 1997 (MIPAr97).

Armenia

Armenian Statistical Service of Republic of Armenia. (n.d.). Supply & Use tables Armenia 2006.

Australia

Australian supply and use tables 1990-2007; Wood, R., Construction, stability and predictability of an input-output time-series for Australia. *Economic Systems Research* **2011,** *23*, (2), 175-211.

Austria

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Belgium

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Bolivia

INSTITUTO NACIONAL DE ESTADÍSTICA. (n.d.). Bolivia: MATRIZ DE INSUMO-PRODUCTO 1999-2002.

Brazil

Lenzen, M.; Pinto de Moura, M. C.; Geschke, A.; Kanemoto, K.; Moran, D. D., A cycling method for constructing input-output table time series from incomplete data. *Economic Systems Research* **2012,** *24*, accepted.

Canada

OECD. (2006). The OECD Input-Output Database: 2006 edition. Retrieved from http://www.oecd.org/sti/inputoutput/

OECD. (2009). The OECD Input-Output Database: 2009 edition. Retrieved from http://www.oecd.org/sti/inputoutput/

Switzerland

Swiss Statistics. (2009). Tableau Input-Output 2001. Retrieved June 3, 2009, from http://www.bfs.admin.ch/bfs/portal/fr/index/themen/04/02/01/dos/02.html

Swiss Statistics. (2009). Tableau Input-Output 2005. Retrieved June 3, 2009, from http://www.bfs.admin.ch/bfs/portal/fr/index/themen/04/02/01/dos/02.html

Chile

Banco Central de Chile. (n.d.). DE LA MATRIZ INSUMO-PRODUCTO 1996.

Banco Central de Chile. (n.d.). Matriz de insumo-producto 2003.

China

National Bureau of Statistics of China. (2006). *Input-output table of China 2002.* Beijing: China Statistical Publishing House.

National Bureau of Statistics of China. (n.d.). Input-output table of China 1990, 1992, 1995, 1997, 2000, 2002, 2005, 2007.

Columbia

Departamento Administrativo Nacional de Estadistica. (n.d.). Matriz de utilización de productos 2000-2007.

Departamento Administrativo Nacional de Estadistica. (n.d.). Matriz oferta de productos 2000-2007.

Czech Republic

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Germany

Statistisches Bundesamt. (n.d.). Input-Output-Tabelle 1991-2006.

Denmark

Statistics Denmark. (2009). Danish annual Input-Output tables 1990 - 2006. Retrieved May 21, 2009, from http://www.dst.dk/HomeUK/Statistics/ofs/NatAcc/IOTABLES.aspx

Ecuador

BANCO CENTRAL DEL ECUADOR. (n.d.). Supply and use table 2000-2007.

Spain

National Statistics Institute. (2010). Spanish National Accounts: Input-output Framework 1995-2006. Retrieved February 15, 2010, from http://www.ine.es/jaxi/menu.do?type=pcaxis&path=/t35/p008&file=inebase&L=1

Estonia

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Finland

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

France

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

UK

Wiedmann, T., Wood, R., Lenzen, M., Minx, J. C., Guan, D., & Barrett, J. (2008). Development of an Embedded Carbon Emissions Indicator. London. Retrieved from http://www.defra.gov.uk/environment/business/scp/research/themes/theme1/scale0708.htm

Office for National Statistics. (2011). United Kingdom Input-Output Analytical Tables 2005. Office for National Statistics.

Georgia

GEOSTAT. (n.d.). Supply and use tables 2006-2008.

Greenland

Statistics Greenland. (1998). Input-output tabeller og multiplikatorer for Grønland 1992.

Statistics Greenland. (n.d.). Input-output tabel for 2004.

Greece

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Hong Kong

Tormey, J. (1993). Creating Synthetic Single Region Input-Output Data for SALTER: Hong Kong and the Rest of the World. Canberra.

Hungary

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Indonesia

IDE-JETRO. (2005). *Asian International I/O Table 2000.*

India

Ministry of Statistics and Programme Implementation. (2009). Input-Output Transactions Table for India 1993-1994. Retrieved June 3, 2009, from http://mospi.nic.in/mospi_cso_rept_pubn.htm

Ministry of Statistics and Programme Implementation. (2009). Input-Output Transactions Table for India 1998-1999. Retrieved June 3, 2009, from http://mospi.nic.in/mospi_cso_rept_pubn.htm

Ministry of Statistics and Programme Implementation. (2009). Input-Output Transactions Table for India 2003-2004. Retrieved June 3, 2009, from http://mospi.nic.in/mospi_cso_rept_pubn.htm

Ministry of Statistics and Programme Implementation. (2009). Input-Output Transactions Table for India 2006-2007. Retrieved June 3, 2009, from http://mospi.nic.in/mospi_cso_rept_pubn.htm

Ireland

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Iran

Statistical center of Iran. (n.d.). INPUT-OUTPUT TABLES FOR IRAN 2001.

Statistical center of Iran. (n.d.). INPUT-OUTPUT TABLES FOR IRAN 1991.

Israel

Central Bureau of Statistics Israel. (2002). Input-Output Tables - 1995. Retrieved from

Central Bureau of Statistics Israel. (2010). Supply and Use Table 2005 and Supply Table 2006-2007. Retrieved October 29, 2010, from http://www.cbs.gov.il/webpub/pub/text_page_eng.html?publ=62&CYear=2007&CMonth=1

Central Bureau of Statistics Israel. (2010). Supply and Use Table 2004 and Supply Table 2005-2006. Retrieved October 29, 2010, from http://www.cbs.gov.il/webpub/pub/text_page_eng.html?publ=62&CYear=2006&CMonth=1

Central Bureau of Statistics Israel. (2010). SUPPLY AND USE TABLE 2000 AND SUPPLY TABLE 1995-2003. Retrieved October 29, 2010, from http://cbs.gov.il/www/publications/supply_tables03/supply_tables_e.htm

Italy

Eurostat. (2009). ESA 95 Supply, Use and Input-Output tables. Retrieved April 30, 2009, from http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks

Japan

Ministry of Internal Affairs and Communications. (1994). 1990 Input-Output Tables for Japan. Research Institute of Economy, Trade and Industry.

Ministry of Internal Affairs and Communications. (1999). 1995 Input-Output Tables for Japan. Research Institute of Economy, Trade and Industry.

Ministry of Internal Affairs and Communications. (2004). 2000 Input-Output Table for Japan. Research Institute of Economy, Trade and Industry.

Ministry of Internal Affairs and Communications. (2009). 2005 Input-Output Tables for Japan. Retrieved May 9, 2009, from http://www.e-stat.go.jp/SG1/estat/List.do?bid=000001019588&cycode=0

Kazakhstan

Müller, M. *Central Asian Input-Output Tables*; Personal communication July 2011; Zentrum für Entwicklungsforschung, Rheinische Friedrich-Wilhelms-Universität: Bonn, Germany, 2011.

Kenya

IFPRI. (2010). Social Accounting Matrices. Retrieved December 17, 2010, from http://www.ifpri.org/

Kyrgyzstan

Müller, M. *Central Asian Input-Output Tables*; Personal communication July 2011; Zentrum für Entwicklungsforschung, Rheinische Friedrich-Wilhelms-Universität: Bonn, Germany, 2011.

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Table S3.2: List of countries in the Eora MRIO database

UN code	Name	Sectors (PR/IN)
4	Afghanistan	26/0
8	Albania	26/0
12	Algeria	26/0
20	Andorra	26/0
24	Angola	26/0
28	Antigua and Barbuda	26/0
32	Argentina	125/196
51	Armenia	26/0
533	Aruba	26/0
36	Australia	345/345
40	Austria	61/61
31	Azerbaijan	26/0
44	Bahamas	26/0
48	Bahrain	26/0
50	Bangladesh	26/0
52	Barbados	26/0
112	Belarus	26/0
56	Belgium	61/61
84	Belize	26/0
204	Benin	26/0
60	Bermuda	26/0
64	Bhutan	26/0
68	Bolivia	37/37
70	Bosnia and Herzegovina	26/0
72	Botswana	26/0
76	Brazil	56/111
92	British Virgin Islands	26/0
96	Brunei Darussalam	26/0
100	Bulgaria	26/0
854	Burkina Faso	26/0
108	Burundi	26/0
116	Cambodia	26/0
120	Cameroon	26/0
124	Canada	49/0
132	Cape Verde	26/0
136	Cayman Islands	26/0
140	Central African Republic	26/0
148	Chad	26/0
152	Chile	75/75
156	China	0/123
170	Colombia	60/60
178	Congo	26/0
188	Costa Rica	26/0
191	Croatia	26/0
192	Cuba	26/0
196	Cyprus	26/0
203	Czech Republic	61/61
384	Côte d'Ivoire	26/0
408	Democratic People's Republic of Korea	26/0
180	Democratic Republic of the Congo, previously Zaïre	26/0
208	Denmark	131/0
262	Djibouti	26/0
214	Dominican Republic	26/0

218	Ecuador	49/61
818	Egypt	26/0
222	El Salvador	26/0
232	Eritrea	26/0
233	Estonia	61/61
231	Ethiopia	26/0
242	Fiji	26/0
246	Finland	61/61
250	France	61/61
258	French Polynesia	26/0
266	Gabon	26/0
270	Gambia	26/0
268	Georgia	47/68
276	Germany	0/72
288	Ghana	26/0
300	Greece	61/61
304	Greenland	31/0
320	Guatemala	26/0
324	Guinea	26/0
328	Guyana	26/0
332	Haiti	26/0
340	Honduras	26/0
344	Hong Kong	38/38
348	Hungary	61/61
352	Iceland	26/0
356	India	116/116
360	Indonesia	0/77
364	Iran	100/148
368	Iraq	26/0
372	Ireland	61/61
376	Israel	163/163
380	Italy	61/61
388	Jamaica	26/0
392	Japan	0/402
400	Jordan	26/0
398	Kazakhstan	0/121
404	Kenya	51/51
414	Kuwait	55/0
417	Kyrgyzstan	89/87
418	Lao People's Democratic Republic	26/0
428	Latvia	61/61
422	Lebanon	26/0
426	Lesotho	26/0
430	Liberia	26/0
434	Libyan Arab Jamahiriya	26/0
438	Liechtenstein	26/0
440	Lithuania	61/61
442	Luxembourg	26/0
446	Macao Special Administrative Region of China	26/0
450	Madagascar	26/0
454	Malawi	26/0
458	Malaysia	0/98
462	Maldives	26/0
466	Mali	26/0
470	Malta	61/61
478	Mauritania	26/0
480	Mauritius	57/67
484	Mexico	80/80
492	Monaco	26/0

496	Mongolia	26/0
499	Montenegro	26/0
504	Morocco	26/0
508	Mozambique	26/0
104	Myanmar	26/0
516	Namibia	26/0
524	Nepal	26/0
528	Netherlands	61/61
530	Netherlands Antilles	16/41
540	New Caledonia	26/0
554	New Zealand	127/210
558	Nicaragua	26/0
562	Niger	26/0
566	Nigeria	26/0
578	Norway	61/61
275	Occupied Palestinian Territory	26/0
512	Oman	26/0
586	Pakistan	26/0
591	Panama	26/0
598	Papua New Guinea	26/0
600	Paraguay	34/47
604	Peru	46/46
608	Philippines	0/77
616	Poland	61/61
620	Portugal	61/61
634	Qatar	26/0
410	Republic of Korea	0/78
498	Republic of Moldova	26/0
642	Romania	61/61
643	Russian Federation	49/0
646	Rwanda	26/0
882	Samoa	26/0
674	San Marino	26/0
678	Sao Tome and Principe	26/0
682	Saudi Arabia	26/0
686	Senegal	26/0
688	Serbia	26/0
690	Seychelles	26/0
694	Sierra Leone	26/0
702	Singapore	154/154
703	Slovakia	61/61
705	Slovenia	61/61
706	Somalia	26/0
710	South Africa	95/96
724	Spain	76/119
144	Sri Lanka	26/0
736	Sudan	26/0
740	Suriname	26/0
748	Swaziland	26/0
752	Sweden	61/61
756	Switzerland	43/43
760	Syrian Arab Republic	26/0
761	Taiwan	0/163
762	Tajikistan	26/0
764	Thailand	0/180
807	Macedonia	61/61
768	Togo	26/0
780	Trinidad and Tobago	26/0
788	Tunisia	26/0

792	Turkey	61/61
795	Turkmenistan	26/0
800	Uganda	26/0
804	Ukraine	0/121
784	United Arab Emirates	26/0
826	United Kingdom	511/511
834	United Republic of Tanzania	26/0
840	USA	429/429
858	Uruguay	84/103
860	Uzbekistan	0/123
548	Vanuatu	26/0
862	Venezuela	122/122
704	Viet Nam	0/113
887	Yemen	26/0
894	Zambia	26/0
716	Zimbabwe	26/0

Table S3.3: Availability of input-output tables

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aruba						x	x	x	x	x	x	x	x								
Netherlands Antilles															x						
Argentina								x													
Armenia																	x				
Australia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
Austria						x		x		x	x	x	x	x	x	x					
Belgium						x		x		x	x	x	x	x	x						
Bolivia										x	x	x	x								
Brazil	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Canada						x					x										
Switzerland												x				x					
Chile							x							x							
China	x		x			x		x			x		x			x		x			
Colombia											x	x	x	x	x	x	x	x			
Czech Republic						x	x	x	x	x	x	x	x	x	x	x					
Germany		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Denmark	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Ecuador											x	x	x	x	x	x	x	x			
Spain	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Estonia								x			x	x	x	x	x	x					
Finland						x	x	x	x	x	x	x	x	x	x	x					
France						x	x	x	x	x	x	x	x	x	x	x					
United Kingdom			x	x	x	x	x	x	x	x	x	x	x	x	x	x					
Georgia																	x	x	x		
Greece											x	x	x	x	x	x	x	x			
Greenland			x												x						
Hong Kong			x																		
Hungary									x	x	x	x	x	x	x	x					
Indonesia											x										
India				x					x					x			x				
Ireland									x		x	x	x			x					
Iran		x										x									
Israel						x	x	x	x	x	x	x	x	x	x	x	x	x			
Italy						x	x	x	x	x	x	x	x	x	x						
Japan	x					x					x					x					
Kazakhstan	x																				

Kenya														x						
Kyrgyzstan												x								
South Korea	x			x		x			x		x					x	x	x		
Kuwait											x									
Lithuania											x	x	x	x	x					
Luxembourg						x	x	x	x	x	x	x	x	x	x	x	x	x		
Latvia							x		x											
Maldives								x												
Mexico														x						
Macedonia																x				
Malta											x	x								
Mongolia																x				
Mauritius								x					x							
Malaysia		x									x									
Netherlands						x	x	x	x	x	x	x	x	x	x	x				
Norway												x	x	x	x	x	x			
New Zealand						x							x					x		
Peru					x															
Philippines											x									
Poland											x	x	x	x	x					
Portugal						x	x	x	x	x	x	x	x	x	x	x	x			
Paraguay					x															
Romania											x			x	x	x				
Russian Federation	x					x					x									
Singapore	x					x					x									
Slovakia						x	x	x	x	x	x	x	x	x	x					
Slovenia											x	x	x	x	x	x				
Sweden						x	x	x	x	x	x	x	x	x	x	x	x			
Thailand	x					x			x		x					x				
Turkey													x							
Taiwan		x			x		x			x		x			x					
Ukraine	x													x	x	x	x	x	x	
Uruguay								x												
USA			x				x	x	x	x	x	x	x	x	x	x	x	x	x	x
Uzbekistan	x																			
Venezuela								x												
Viet Nam							x				x							x		
South Africa				x					x	x	x		x							

Text S4 *Appendix for* International trade undermines emission reduction targets: New evidence from air pollution

Text S4.1 Data Sources

All GHG emissions are reported exclusive of land use change. Results online at http://worldmrio.com are available both inclusive and exclusive of land use change. We do not account for land use change as a GHG sink.

The sources for energy and emissions data used in this study are:

Energy

Agency for Natural Resources and Energy. (2009). Energy Balance Tables. Retrieved November 18, 2009, from
http://www.enecho.meti.go.jp/info/statistics/jukyu/result-2.htm

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European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). (2012) Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. http://edgar.jrc.ec.europa.eu

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Carbon Dioxide Information Analysis Center Oak Ridge National Laboratory. (2012). National CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2006. doi:doi 10.3334/CDIAC/00001

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Air pollution

European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). (2012) Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. http://edgar.jrc.ec.europa.eu

Eurostat. (2009). Air Emissions Accounts by activity (NACE industries and households). Retrieved from http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/data/database

Ozone depleting substances

United Nations Environment Programme. (2012) Data Access Centre. Retrieved May 9, 2012, from
http://www.dst.dk/HomeUK/Statistics/ofs/NatAcc/IOTABLES/emmissions.aspx

Note: While the data sources used for air pollution and ozone depleting substance emissions are authoritative, we note that these data may not be tracked as closely or comprehensively as GHG emission data and thus may be subject to higher uncertainty.

Table S4: Tables of top shifting sectors and paths

Table S4.1: Top 25 shifting sectors, by country of final consumption

Mt CO_2	Sector in which CO_2 emissions occurred	Country of final consumption	Consumer country is Kyoto Annex I?
52.7	China Commodities Electricity and steam production and supply	USA	y
47.5	China Commodities Electricity and steam production and supply	Japan	y
33.6	China Commodities Electricity and steam production and supply	Hong Kong	
30.5	China Commodities Electricity and steam production and supply	UK	y
24.6	China Commodities Electricity and steam production and supply	Germany	y
21.0	China Commodities Electricity and steam production and supply	South Korea	
14.3	China Commodities Electricity and steam production and supply	Italy	y
14.3	China Commodities Electricity and steam production and supply	France	y
10.6	India Industries Electricity	USA	y
10.2	China Commodities Electricity and steam production and supply	Netherlands	y
10.0	China Commodities Electricity and steam production and supply	Canada	y
9.6	China Commodities Electricity and steam production and supply	India	
9.5	China Commodities Electricity and steam production and supply	Singapore	
8.5	India Industries Electricity	UK	y
8.3	China Commodities Electricity and steam production and supply	Spain	y
7.9	India Industries Electricity	China	
7.9	China Commodities Electricity and steam production and supply	Malaysia	
7.9	China Commodities Electricity and steam production and supply	Mexico	
7.4	USA Industries Truck transportation	UK	Y
7.3	South Korea Commodities Electric services	China	
7.1	Russia Industries Production, collection and distribution of electricity	China	
6.9	China Commodities Electricity and steam production and supply	Brazil	
6.8	China Commodities Cement and cement asbestos products	USA	y
6.5	China Commodities Electricity and steam production and supply	Australia	y
6.3	China Commodities Coal mining and processing	Japan	y

Table S4.2: Top 25 shifting sectors, by sector of final consumption

Mt CO_2	Sector in which CO_2 emissions occurred	Country and sector of final consumption
9.1	China Commodities Electricity and steam production and supply	Hong Kong Commodities trade and transport
7.2	China Commodities Electricity and steam production and supply	Hong Kong Commodities wearing apparels
6.9	China Commodities Electricity and steam production and supply	Hong Kong Commodities construction
3.6	China Commodities Electricity and steam production and supply	USA Commodities Light truck and utility vehicle manufacturing
3.5	China Commodities Electricity and steam production and supply	Germany Commodities Passenger cars and parts
3.2	China Commodities Cement and cement asbestos products	Hong Kong Commodities construction
2.6	China Commodities Electricity and steam production and supply	USA Commodities General state and local government services
2.6	China Commodities Electricity and steam production and supply	USA Commodities Retail trade
2.6	China Commodities Other textiles not elsewhere classified	Hong Kong Commodities wearing apparels
2.5	China Commodities Electricity and steam production and supply	South Korea Commodities Radio, television and comm. equip.
2.4	China Commodities Electricity and steam production and supply	Germany Commodities Re-export
2.4	China Commodities Electricity and steam production and supply	USA Commodities Residential permanent site structures
2.4	China Commodities Electricity and steam production and supply	USA Commodities General Federal defense government services
2.4	China Commodities Electricity and steam production and supply	USA Commodities Automobile manufacturing
2.3	China Commodities Electricity and steam production and supply	Hong Kong Commodities machinery and equipment
2.3	India Industries Electricity	China Commodities Construction
2.2	China Commodities Electricity and steam production and supply	USA Commodities Other nonresidential structures
2.2	China Commodities Electricity and steam production and supply	South Korea Commodities Civil Engineering
2.2	Russia Industries Production, collection and distribution of electricity	China Commodities Construction
2.1	South Korea Commodities Transportation and warehousing	USA Commodities General Federal defense gov. services
2.1	China Commodities Electricity and steam production and supply	Hong Kong Commodities other manufacturing
2.1	China Commodities Electricity and steam production and supply	Japan Commodities Wholesale trade
2.1	China Commodities Electricity and steam production and supply	Netherlands Commodities Re-export
2.1	China Commodities Cotton textiles	Hong Kong Commodities wearing apparels
2.0	China Commodities Electricity and steam production and supply	Canada Industries Construction

Table S4.3: Top 25 shifting sectors, by export to Kyoto Protocol Annex I or non-Kyoto Protocol Annex I countries

Mt CO_2	Sector in which CO_2 emissions occurred	Consumption (Annex I or not)
271.5	China Commodities Electricity and steam production and supply	Annex I
156.6	China Commodities Electricity and steam production and supply	Non-Annex I
57.5	India Industries Electricity	Annex I
46.6	India Industries Electricity	Non-Annex I
32.2	China Commodities Highway freight and passengers transport	Annex I
31.2	USA Industries Truck transportation	Non-Annex I
30.2	USA Industries Truck transportation	Annex I
27.7	China Commodities Cement and cement asbestos products	Annex I
27.1	China Commodities Petroleum refining	Annex I
21.7	China Commodities Water freight and passengers transport	Annex I
20.0	USA Industries Natural gas distribution	Non-Annex I
19.1	USA Industries Electric power generation, transmission, and distribution	Non-Annex I
18.5	USA Industries Electric power generation, transmission, and distribution	Annex I
18.3	China Commodities Highway freight and passengers transport	Non-Annex I
17.1	China Commodities Cement and cement asbestos products	Non-Annex I
16.8	USAUSA Industries Natural gas distribution	Annex I
16.7	Kazakhstan Commodities Power	Annex I
16.2	China Commodities Petroleum refining	Non-Annex I
15.2	Saudi Arabia Industries Electricity, Gas and Water	Annex I
15.0	China Commodities Gas production and supply	Annex I
14.0	Taiwan Commodities Electricity	Non-Annex I
13.4	China Commodities Coal mining and processing	Annex I
13.3	China Commodities Water freight and passengers transport	Non-Annex I
13.3	Taiwan Commodities Electricity	Annex I
12.9	South Korea Commodities Electric services	Non-Annex I

S4.4: List of countries included

Developed countries (Listed in Annex B of the Kyoto Protocol)	**Emission limitation or reduction target listed in Annex B of the Kyoto Protocol'**
Austria	8%
Belgium	8%
Bulgaria	8%
Czech Republic	8%
Denmark	8%
Estonia	8%
Finland	8%
France	8%
Germany	8%
Greece	8%
Ireland	8%
Italy	8%
Latvia	8%
Liechtenstein	8%
Lithuania	8%
Luxembourg	8%
Monaco	8%
Netherlands	8%
Portugal	8%
Romania	8%
Slovakia	8%
Slovenia	8%
Spain	8%
Sweden	8%
Switzerland	8%
United Kingdom	8%
United States of America	7%
Canada	6%
Hungary	6%
Japan	6%
Poland	6%
Croatia	5%
New Zealand	0
Russian Federation	0
Ukraine	0
Norway	+1%
Australia	+8%
Iceland	+10%

In addition to these 38 countries the Eora MRIO used defines149 additional countries which we refer to as developing countries. The complete list of countries included in the Eora MRIO is:

Afghanistan, Albania, Algeria, Andorra, Angola, Antigua, Argentina, Armenia, Aruba, Australia, Austria, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belgium, Belize, Benin, Bermuda, Bhutan, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, British Virgin Islands, Brunei, Bulgaria, Burkina Faso, Burundi, Cambodia, Cameroon, Canada, Cape Verde, Cayman Islands, Central African Republic, Chad, Chile, China, Colombia, Congo, Costa Rica, Croatia, Cuba, Cyprus, Czech Republic, Cote d'Ivoire, North Korea, DR Congo, Denmark, Djibouti, Dominican Republic, Ecuador, Egypt, El Salvador, Eritrea, Estonia, Ethiopia, Fiji, Finland, France, French Polynesia, Gabon, Gambia, Georgia, Germany, Ghana, Greece, Greenland, Guatemala, Guinea, Guyana, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Laos, Latvia, Lebanon, Lesotho, Liberia, Libya, Liechtenstein, Lithuania, Luxembourg, Macao SAR, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Monaco, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nepal, Netherlands, Netherlands Antilles, New Caledonia, New Zealand, Nicaragua, Niger, Nigeria, Norway, Gaza Strip, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, South Korea, Moldova, Romania, Russia, Rwanda, Samoa, San Marino, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Singapore, Slovakia, Slovenia, Somalia, South Africa, Spain, Sri Lanka, Suriname, Swaziland, Sweden, Switzerland, Syria, Taiwan, Tajikistan, Thailand, TFYR Macedonia, Togo, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, UAE, UK, Tanzania, USA, Uruguay, Uzbekistan, Vanuatu, Venezuela, Viet Nam, Yemen, Zambia, Zimbabwe

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